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CAN THE VELOCITY OF PROPAGATION OF RADIO WAVES BE MEASURED BY SHORAN?

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Abstract--The velocity of light and the velocity of propagation of radio waves are theoretically identical in vacuo. With refined methods of utilizing radar, long distances can be measured with considerable accuracy. This paper describes the methods used to measure 47 lines varying in length from 67 mi to 367 mi. Six of the lines measured could be compared with geodetic distances obtained from first-order triangulation. The entire network of lines was so designed that a rigid adjustment could be made. From the comparison with the six geodetic lengths and from an adjustment of the 41 other lines, a value of the velocity of propagation of radio waves in vacuo is deduced which exceeds by 16 km/sec the Anderson value of velocity of light in vacuo of 299,776 km/sec. All sources of error are discussed.

Introduction--The velocity of light has been determined from time to time since Cornu's experiments in 1872. DORSEY [1944] states "those values . . . . . have, in general, decreased monotously from Cornu's 300.4 megameters per second in 1874 to Anderson's 299.776 in 1940, the monotony being severely broken by the presence of Perrotin and Prim's 299.90 of 1902, between the adjacent values by Michelson, 299.853 in 1882 and 299.802 . . . . . in 1924."

Once again the monotony is being broken, but the more recent methods are the direct methods of the engineer rather than the laboratory methods of the physicist, and it is the velocity of propagation of radio waves which is being investigated. Theoretically, the velocities of propagation of radio waves and of light waves do not differ in vacuo, but the engineer prefers to measure directly the quantity that he wishes to determine. Utilizing a previously determined velocity of light, it may now be possible to use engineering methods of a simple nature to determine the velocity of propagation of radio waves by successive approximations.

The writer began his preliminary tests to utilize shoran to measure long distances with geodetic accuracy during World War II as a project of the United States Army Air Forces [ASLAKSON and RICE, 1946]. At about the same time the British noted that their observations with Oboe, a system comparable with shoran in accuracy, agreed better with triangulated distances if the Michelson value of 1935 (299,774 km/sec) were increased by 13.6. ESSEN [1947] deduced a value of 299,793 from a series of experiments. Essen measured the electrical resonance of a wave guide of short length and stated that his probable error, in what he described as a preliminary determination, was ± 9 km/sec. BERGSTRAND [1948] published a value of 299,796. Bergstrand used a "geodimeter" designed for direct distance measurement, utilizing the Kerr cell and photo tube principle. All three determinations mentioned above agree much better with Michelson's 1926 observations than with his 1935 work.

The British determinations during World War II were made by Jones and Cornford HART, 1948 by flying a Mosquito aircraft across an extended base line between two geodetic stations, as nearly as possible on a predetermined tracking range. Sea-level values were also observed over three sea paths of 1.9475, 31.4318, and 42.0960 mi from a station in North Devon. In the British experiments a mean linear lapse rate of the coefficient of refraction with altitude was assumed.

Also in Italy during the latter stages of the War, a distance of 618 km was measured by shoran. In this experiment the airplane was flown 22 times across the line between the ground stations. During each crossing the minimum distance was observed, and later reduced to sea-level distance. The altitudes were 11,000 and 15,000 ft. This work is described briefly by Hart who notes that if Essen's deduced velocity of 299,793 were used instead of the 299,776 for which the shoran computer is designed, the discrepancy would be reduced from +45 to +5 meters.

In the work under the direction of the writer which began with preparations and preliminary tests in 1943 and ended in 1947, refinements not made by Jones and Cornford and not used in the shoran measurements in Italy were incorporated in the observational, calibrational, and computational techniques. Studies of systematic errors were made and elaborate calibrational procedures were devised.

Although the observations agreed excellently among themselves, a systematic discrepancy with the geodetic distances between triangulation stations was noted. This lack of agreement largely disappears if a velocity of 299,792 km/sec is assumed. This is exactly the mean of the values of Jones and Cornford, Essen, and Bergstrand.

As stated above, V, the value of velocity in a vacuum, was taken as 299,776 km/sec in the instrument design. Converted to conventional units used in the United States, V is equal to 186,271.8 mi/sec. The principle of the shoran disign is satisfied for distance when the timing frequency in cycles/sec is equal to one half the velocity of electromagnetic propagation in mi/sec, or

$$f_t = V_t/2$$

where f_t = the frequency of the timing crystal and V_t = 1/2 travel time of the impulse in mi/sec.

The electromagnetic impulse actually travels through air of changing density and changing moisture content which change the velocity of propagation from point to point along its path. The velocity of propagation in air is given by

$$v = VK_1^{-1/2}$$

where v is the velocity of propagation in air, V is the velocity in a vacuum, and K_1 is the static dielectric constant of the air. K_1 varies from unity in empty space to K_s = 1.000567 for standard dry atmospheric conditions. The value of K_s adopted above is discussed later in this paper.

Therefore if V_s if considered the velocity of propagation of an electromagnetic wave through dry air under standard gas conditions, assuming V to be 299,776 km/sec,

$$V_s = 186{,}271.8/1.0002835 = 186{,}219.0 \text{ mi/sec}$$

The correct timing frequency should therefore be 93,109.5 cycles/sec if the above velocity is assumed. The calibration of this frequency is discussed later.

The design velocity of 299,776 km/sec was not seriously questioned by the project staff during the search for the systematic error with distance which continued to become more systematic with each refinement in calibrational and operational technique.

A comparison was finally made with three geodetic distances based on triangulation which had been executed by another organization. When these lines were measured, the discrepancies did not vary directly with distance. It has recently been revealed that the second group of triangulated lines contains a base-to-base length error of a magnitude that makes it unusable as a standard. This second network is now being reobserved with triangulation observations of a higher order. Meanwhile, the original shoran velocity data have once again been studied to ascertain the cause of the systematic error proportional to distance.

The problem was approached independently by two different persons. The writer based his investigation on a comparison of the shoran distances with the geodetic distances derived from the United States Coast and Geodetic Survey first-order triangulation, and it will be described first. The second method is described on pages 484 and 485

Before discussing the investigations, however, it is desirable to review very briefly the methods of observation when using shoran.

Methods of observation--In geodetic operations, shoran readings are used to determine the minimum sum of the distances from the airplane to two ground stations, and a scheme of triangulation is built up from these sum distances, no angles being measured (see Fig. 1).

The important refinements over previous shoran distance measurements were in the use of (a) a line-crossing technique designed to eliminate observer's errors, (b) least-squares computation of the minimum sum distance, (c) refined methods of determining the altitude of the airplane, (d) a velocity correction based on actual airplane weather reconnaissance at the time of the line-crossing measurements, (e) refinements in the geometric corrections for the reduction of the slant shoran distances to sea-level distances or to the approximate geodesic, and finally, (f) extensive instrument research which resulted in numerous modifications of the shoran system. The most important of these was the discovery of an error which was due to changes in the intensity of the signal and the design of a method to correct for this error. Many of the instrumental changes were suggested by

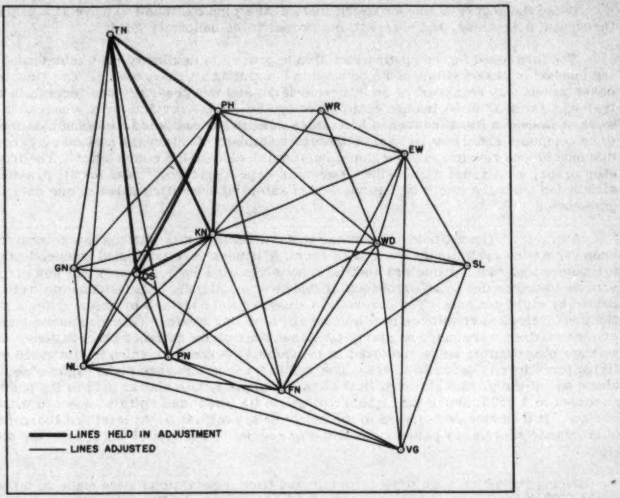

Fig. 1--Shoran network of 47 lines; the six heavy lines indicate those on which geodetic measurements were also made

Stuart W. Seeley of the Radio Corporation of America, the inventor of shoran.

A complete and detailed description of the methods is contained in a three-volume report which has not yet been released; the following material is, therefore, greatly abbreviated.

In an earlier paper [ASLAKSON and RICE, 1946], the preliminary measurement methods used at Denver were discussed. That work was experimental and is not considered here.

Line flying technique--The first step was to determine the minimum sum of two shoran distances from the plane to each of two ground stations as the plane crossed the line between the stations. The new technique was designated as the "Figure-8" line-crossing method. Four line-crossings made in the following manner constituted a "set of observations." All four crossings in a set were flown as nearly as possible at the same altitude and as nearly as possible halfway between the ground stations.

(1) The first crossing was made at approximately a 12°.5 angle to the normal.

(2) A second crossing was made from the opposite side of the line also at a 12°.5 angle to the normal but on the opposite side.

(3) The third crossing was made over about the same path as the second but in the opposite direction.

(4) The fourth crossing was made over the same path as the first crossing but in the opposite direction.

The new technique was effective in reducing the error caused by the observer's tendency to lag or lead in making a coincidence on the moving "pips." The Figure-8 method is analogous to the reversal method of observation in direction measurement with a theodolite and also to the spacing of the initial readings over various parts of the circle to eliminate errors due to eccentricities of the circle. Previously the lines had been crossed on a course normal to the line between the ground stations. In the original procedure the distances to the stations decreased until the minimum was reached and then began increasing. This caused the pips to slow down, come to a dead stop, and then change direction. The uncertainty of the observer as to when the exact minimum was reached resulted in ragged readings in the vicinity of the very critical minimum.

Using the Figure-8 line-crossing method, the pips continued to move at a nearly uniform rate throughout a crossing, and observations proved to be uniformly good

The form used for computing was also improved in flexibility. It was extended so that a varying number of observations could be used in computing a line-crossing. The time interval between observations was regulated by an intervalometer and was generally two seconds between successive frames. From 20 to 50 frames could be computed on the revised form, whereas in the preliminary work at Denver a fixed number of 31 frames was always computed. Inasmuch as the number of frames to be computed could now be varied, the exact number of intervals necessary to cover one mile of distance or one revolution of the goniometer was selected for computation. The troublesome goniometer error, sometimes called the "one-mile repeating error," was for all practical purposes eliminated from the result by this method of sampling the entire range of one complete cycle of the goniometer.

Altimetry--The altitude of the plane was determined with much greater accuracy than it had been during the preliminary work at Denver. Altitudes were computed independently from barometric altimeters and radio altimeters and the results verified the conclusion that any error in the reduced shoran distances due to an erroneous altitude was negligible. All instruments were carefully calibrated by rigid methods. The barometric altitudes were refined by observation of the lapse rate of the meteorological conditions by a second airplane or "weather reconnaissance plane." The weather observations were made at nearly the same time as the distance observations. Inasmuch as the weather observations were also used in the velocity correction which is discussed next, the entire flying procedure is described here. The weather reconnaissance plane began observations 500 ft above one of the ground stations, flew along the approximate shoran path to the point of line crossing, ascended to 1,000 ft above the highest altitude to be flown, and spiraled down to within 500 ft of the surface. It then spiraled upward to the height of the highest flight level and thereafter followed the approximate shoran ray path on a descending course to a height of 500 ft over the second ground station.

During the entire time psychrometric and time observations were made at 500-ft intervals up to the 5000-ft level, and at 1000-ft intervals above that level. The altitude of the shoran line-crossing plane was then computed from the following data: (1) Barometric altimeter and radio altimeter readings which were recorded photographically for each line-crossing. (2) Observed surface pressure and wet and dry bulb thermometer readings. (3) The intermediate psychrometric observations made by the weather reconnaissance airplane during the up-and-down spiral at the point of line-crossing.

The velocity correction--The psychrometric observations by the weather reconnaissance plane described in the preceding section were used to compute a velocity correction. In order to utilize the single parameter K to combine the effect of P, T, and e, the following relationship was employed.

$$\Delta K \times 10^6 = 567 - 152.86\ P/T + 17.85\ e/T - 75.34e\ (T/100)^{-2} \ldots\ldots\ldots\ldots (1)$$

where P = total pressure in millibars, e = partial pressure of water vapor in millibars, T = the absolute temperature (273°.16 C), and $\Delta K = (K_s - 1) - (K - 1)$. K_s is the dielectric constant of standard dry air (1.000567 at 760-mm pressure and 0°C) and K is the dielectric constant of the actual air as computed from (1).

For the small range of K encountered in shoran work the change in the velocity between any two conditions is a linear function of (K - 1). Therefore any deviation from the standard atmospheric conditions assumed in the construction of the shoran computer causes a velocity deviation that is directly proportional to the corresponding deviation in (K - 1) from the value (K_s - 1) assumed in the construction of the computer. The value of 1.000567 for standard dry air was based on the work of Hector and Woernley at the University of Buffalo in 1945 and was adopted instead of 1.000590 which had been used in the earlier work at Denver.

The value of the velocity correction ΔS was then determined from the following relationship.

$$\Delta S = (1/2)\int_0^S \Delta K\, dS \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

A numerical integration procedure was devised to compute the velocity correction, using the values of ΔK computed at appropriate intervals from the weather reconnaissance plane data and increments of the distance at the corresponding points along selected ray paths which approximated the actual ray path. Extensive use was made of tables, particularly "Ray-path tables" from which the distance increments needed in the numerical integration could be quickly interpolated for any path that would actually be flown.

During the preliminary work at Denver a "standard atmosphere" for the area was assumed and the velocity corrections were obtained from tables computed for that standard. Thus the new technique was a decided improvement over the original precedure.

Geometric corrections--The relationship employed to compute the reduction of the shoran distance to the sea-level or map distance was refined to introduce small tabulated corrections for all approximations made in the development. It has been thoroughly investigated and can be considered as rigid.

Instrumental research and corrections--Extensive research in shoran measurements made over a two-mile base with a ground station on an extension of the base and at a surveyed distance from its end, furnished valuable information which enabled many errors of the original shoran bombing instruments to be removed or greatly minimized by electronic modifications. The ground stations were also calibrated over the base, several calibrations of each ground station being made during the progress of the project. The timing crystals were also calibrated to an accuracy of the order of one part in one million.

The Anderson value of velocity was incorporated in the shoran computer by the use of a crystal with a frequency of 93,109.5 cycles/sec or one-half of the velocity of light (Anderson) of 186,219.0 statute mi/sec at 0°C and 760 mm pressure (dry air). The calibration determined the crystal frequency to be 93,109.65 cycles/sec and the difference of 0.15 cycles/sec was used to correct the results according to the following relationship:

$$\Delta S_t = S_t \Delta f / 93{,}109.5 \qquad (3)$$

where ΔS_t = the correction to the shoran distance due to the crystal error, S_t = the measured shoran distance, and Δf = the above difference of 0.15 cycles/sec. The crystals were calibrated by the standard frequencies of the National Bureau of Standards' broadcast over WWV.

The airborne zero correction (essentially an index correction) and the ground-station calibration correction were applied to each shoran distance. Other investigations too numerous to describe here resulted in many modifications which improved instrumental accuracy.

Signal-intensity correction--The somewhat erratic variations in the results obtained on the Denver project were not understood until after the completion of that project. As the result of a conference between Carl Jacobsen and William Adkisson, the electronics engineers of the Project Staff, and Stuart W. Seeley of the Radio Corporation of America, the conclusion was reached that there was an error of considerable magnitude in shoran measurements arising from the fact that the slope of the received pulse varied with signal intensity. A timing error which was a function of signal strength was strongly indicated. A long series of tests proved this to be true, but the problem of elimination seemed insurmountable. Redesign of the equipment was impossible in the alloted time. The comparatively good final results of the Denver project were apparently due to the fact that so many measurements were made over an extended period of time that the signal-intensity error was partly eliminated by multiple observations under many varying conditions of signal intensity. But to be economical and practical in a regular field project, the number of observations had to be reduced. Inasmuch as the instrument could not be redesigned in the time available, a means of correcting for the signal-intensity error was sought.

A standard Air Forces instrument used to observe relative signal strength was modified and calibrated. The signal intensity, I, was observed for each observation. In the southwest corner of the scheme (see Fig. 1), where the first observations were made, only one signal intensity to each ground station was observed for each set of Figure-8's. Later the equipment was modified so that the signal intensity from each station could be observed simultaneously with the line measurement, thus making eight intensity observations for each set of Figure-8's. The fewer intensity measurements in the early part of the project may account for the larger corrections which are found in the southwest corner of the scheme and which are discussed later.

A total of 139 values of I were observed. Each pair of values at any given altitude gave a slope at the approximate mid-point between the two intensity values. Thus, an empirical relationship between error and signal intensity could be determined by least squares. The following equation resulted:

$$\text{I. C.} = K + 0.10629\, I \qquad (4)$$

where I. C. is the signal-intensity correction expressed in units of 0.0001 and K is a constant for zeroing the curve.

The value of K was determined by two methods and was found by each method to be so close to zero as to be negligible. One method of determining K was to place a constant term in the least-squares adjustment of the triangulation network for each line. The second method was called the "sliver-triangle analysis" and is discussed later.

The spread of the observations was materially reduced by applying the signal-intensity correction and this was accepted as evidence of its validity. The intensity corrections were not related to the length of line but were a function of the altitude of the plane and the distance from the line joining the stations. Actual surveys of the intensity lobes were made at several times and they showed that the shape of the lobes conformed very closely with theory. In fact, a method of predicting the altitude to fly to produce given signal intensities proved very successful. In this system of prediction, the altitudes of the airplane and ground stations, the distances from the airplane to the ground stations, and the type of reflecting surface were considered. Jacobsen developed simple nomograms for making the predictions.

Sliver-triangle analysis--If there is a constant error K in any measurement and a distance is measured as a whole and also in two parts, the sum of the latter two measurements will differ from the whole measurement by the constant error K. Similarly in the case of any very long, thin, or sliver triangle found in shoran, the short sides can be projected onto the long side and value of K can be determined. The relationship may be expressed as follows.

$$K = \Delta L/[1 - (\cos A + \cos B)] \quad \text{.....................(5)}$$

where A and B are the acute angles and ΔL is the difference between the long side and the sum of the two short sides projected onto the long side. For the purpose of this study, a large number of sliver triangles were inserted in the shoran scheme because they impose a most rigid condition in the adjustment, a fact quite contrary to ground triangulation. Sixteen such triangles were analyzed with the following result: K (by sliver triangles) = + 0.0008 mi; K (from adjustment) = + 0.00004 mi. Inasmuch as the probable error of each value was slightly greater than the value of K it was assumed that any constant error was negligible and K was accepted as zero.

It should be noted that a sliver-triangle analysis serves somewhat the same purpose as triangle closures in conventional triangulation, as an approximate check in detecting faulty observations during the progress of the field work.

Results of comparison of shoran measurements with inversed first-order triangulation distances --Using the methods described in the preceding paragraphs all six lines of a quadrilateral and its diagonals were measured by shoran. The results are tabulated in Table 1.

It may be noted that a complete set of observations by the Figure-8 method, or four crossings in all, must be used as a unit. All observations in a set must be made by the same operator. The observational procedure thus removes the personal equation of an observer, such as leading or lagging behind the pip during coincidence. With three sets of observations an average of between 700 and 800 individual distance readings are utilized. Each operator also reads his own zero, so the personal equation tends to be eliminated. A marked difference in results between observers was sometimes noted on the preliminary project at Denver, but an elaborate study of the later project failed to show any such difference. The consistency between sets is remarkable, the maximum deviation from the mean being 0.0025 mi or about 0.0042 km. The mean deviation is ± 0.0013 mi or 0.0021 km. The numbers 4.2 and 2.1 represent deviations of observational results in the sixth digit and may be compared with the 35 and 14 in Table 2 which lists Anderson's observations. It seems justifiable to conclude that the shoran observations were more uniform than Anderson's observations.

Furthermore, the means of sets of shoran observations repeated on different days showed smaller differences than individual sets observed on the same day. This is illustrated in Table 3 which lists all lines on which measurements were made on different days. It will be noted that excepting the single observation on January 22, 1947 on the line PH-FN, the agreement between the results on different days is excellent. The mean range or spread is 0.0014 mi. This indicates close agreement regardless of whether the observations were repeated on the same days or on different days.

The internal consistency of the shoran observations being of such a high order, it was a shock to the writer and his staff to find such large differences between the shoran distances and the geodetic distances computed from United States Coast and Geodetic Survey triangulation as listed in

Table 1--Shoran measurements of geodetic lines

Line	Designation	Identifying altitude[a]	Distance[b]	Signal Intensity Correction	Corrected Distance	Mean	Deviation from mean
		ft	mi	mi	mi	mi	mi
1	OS-KN	2,300	101.9151	0.0102	101.9253		-0.0012
		2,500	101.9161	0.0111	101.9272		+0.0007
		2,600	101.9180	0.0091	101.9271	101.9265	+0.0006
2	KN-PH	12,000	139.0453	0.0110	139.0563		-0.0007
		3,600	139.0516	0.0079	139.0595		+0.0025
		4,100	139.0452	0.0125	139.0577		+0.0007
		5,700	139.0402	0.0144	139.0546	139.0570	-0.0024
3	TN-PH	4,000	143.5808	0.0094	143.5902		-0.0009
		6,300	143.5748	0.0177	143.5925		+0.0017
		7,900	143.5755	0.0150	143.5905	143.5911	-0.0006
4	OS-PH	10,700	208.7168	0.0162	208.7330		+0.0014
		8,800	208.7151	0.0148	208.7299		-0.0017
		8,000	208.7201	0.0118	208.7319	208.7316	+0.0003
5	TN-KN	16,400	227.1233	0.0109	227.1342		+0.0012
		13,300	227.1253	0.0065	227.1318	227.1330	-0.0012
6	TN-OS	22,400	235.6500	0.0064	235.6564		-0.0020
		23,100	235.6536	0.0067	235.6603	235.6584	+0.0019

Average deviation from mean ± 0.0013

[a] In computations, a more exact altitude was used for each line crossing.

[b] Distance, based on Anderson's value of 299,776 km/sec, reduced to geodetic or sea-level distance with all corrections applied except signal-intensity correction. Each distance listed is the mean of four line crossings of the Figure-8 method and each line crossing utilized about 30 recorded distances for each station, or about 60 distances in all. Thus about 240 readings, read from 35-mm photographic-recorder film, usually photographed at two-second intervals, enter into each distance listed.

Table 4. It was noted that the differences tended to be proportional to distance but, as stated in the Introduction, three additional measured lengths connected to the triangulation of another organization failed to show the same correlation. The shoran measurements, of course, were questioned. It is now certain that the triangulation containing the doubtful connections was of too low an order to be used as a standard, so another investigation was made to ascertain the cause of the systematic error. The writer was much encouraged by the recent work of Essen and Bergstrand and by the fact that the British on the basis of the limited Oboe experiment did not hesitate to question the Anderson value.

Discussions of error--In tracing the source of the systematic error, the first point to note is that it is evidently at least approximately proportional to the distance. This can be seen in Table 4, where the residuals tend to be proportional to the lengths. (It should be noted further that the smallest of these residuals is more than four times the average deviation of an individual line measurement from the mean.) The same conclusion can be reached from the other lines of the figure not common to Coast and Geodetic Survey triangulation, if we bear in mind that the effect of a change in velocity is to change the scale of the figure. It follows that an erroneous velocity will not introduce any internal discrepancies in the figure, except in the neighborhood of ties to fixed points. On the other hand, an erroneous constant correction to all lengths will introduce closures, especially in the sliver triangles. The failure to find any significant value of K, either from the sliver triangles or from the general solution, indicates that no appreciable systematic error in the form of a constant affecting all lengths can exist in the present techniques. Furthermore, a constant error larger than 0.0036, even with different signs for different stations, is extremely unlikely to exist in the solution, for this value represents the total probable error deduced from the least-squares solution. This amount is roughly one third of the average discrepancy of 0.0094 found. We conclude that the error must be at least roughly proportional to the distance and that no significant constant error exists.

Table 2--Table of Anderson's values of 1939-1940[a]

Date	Weight	Mean velocity in vacuum	Average deviation from mean	
			Daily	Final
		km/sec	km/sec	km/sec
1939				
May 21	20	299,774	7	2
Nov. 8	17	299,775	9	1
13	35	299,759	10	17
15	79	299,772	9	4
16	140	299,780	8	4
27	103	299,781	13	5
1940				
Jan. 10	39	299,774	5	2
23	46	299,774	3	2
Mar. 4	30	299,757	3	19
7	56	299,745	9	31
8	257	299,754	3	22
11	147	299,749	9	27
Apr. 4	348	299,808	9	32
5	122	299,774	10	2
8	125	299,769	7	7
9	197	299,771	7	5
June 15	322	299,801	19	25
16	94	299,775	1.4	1
21	148	299,768	18	8
July 1	293	299,789	12	13
7	147	299,741	3	35
8	130	299,758	9	18
	2,895	299,776	9	14

Estimated dubiety ± 14

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[a] See DORSEY [1944].

An error varying with the distance could be attributed to any of the following causes: (1) A scale error in the goniometer, which measures the time taken for the pulse to travel the distance. (2) A scale error in the first-order triangulation of the United States Coast and Geodetic Survey. (3) An error in the meteorological data or its mathematical use. (4) An error in the physical constant employed to compute the dielectric constant of air. (5) An error in the signal-intensity correction. (6) An error in the velocity of propagation.

Under (1) the goniometer measures the time of travel of the pulse by measuring the phase difference (in terms of a vibration of 93,109.5 cycles/sec) between the instant when pulse A returns to the airborne set and the instant when pulse B is sent out. Between pulse A and pulse B, a large number of other pulses have been sent out, a number, in fact, equal to the number of statute miles between the ground station and the airborne station, provided that the crystal is accurately tuned. The goniometer also counts these pulses. Thus the possible errors of the goniometer are in three parts: first, those due to an error in the pulse repetition rate; second, the error of counting pulses; and third, a periodic error, called the "one-mile goniometer error." The counting errors are practically negligible; and the one-mile periodic error, which is quite appreciable, was eliminated, first by direct calibration on a known ground course, and second by an oblique line-crossing technique which spread the readings on both goniometers completely around the dial, so that they averaged out. In any case, no periodic error of this type could be mistaken for an error proportional to the distance. The pulse repetition rate is controlled by the airborne crystal oscillator. This, in turn, was constantly checked by a temperature-controlled crystal at the ground station, which was repeatedly calibrated against WWV. It is generally considered that errors with this technique should not exceed one part in one million.

With regard to the second source of error cited, reference is made to Special Publication No. 108 of the U. S. Coast and Geodetic Survey, which contains a discussion of the errors of the triangu-

Table 3--Shoran measurements repeated on different days

Name	Date	Altitude	Shoran distance	Mean	Difference between means
		ft	mi	mi	mi
EW-SL	Mar. 8, 1947	3,800	147.8680		
		4,300	147.8649		
		5,700	147.8610	147.8646	
	Mar. 14, 1947	3,800	147.8694		
		4,400	147.8645		
		5,800	147.8606	147.8645	+0.0001
PN-VG	Jan. 31, 1947	13,400	278.9814		
		14,000	278.9867	278.9840	
	Feb. 19, 1947	15,800	278.9835	278.9835	+0.0005
NL-PH	Dec. 14, 1946	21,400	331.3051	331.3051	
	Dec. 17,1946	23,000	331.3070		
		24,400	331.3050	331.3060	-0.0009
NL-KN	Jan. 8, 1947	11,100	214.7972		
		11,500	214.8068		
		11,900	214.7892	214.8007	
	Jan. 22, 1947	12,000	214.8040	214.8040	-0.0033
GN-KN	Dec. 13, 1946	5,900	163.2812		
		3,900	163.2849		
		8,000	163.2793	163.2818	
	Jan. 14, 1947	5,900	163.2823	163.2823	-0.0005
PH-FN	Jan. 22, 1947	20,700	321.0300	321.0300	
	Jan. 23, 1947	24,100	321.0341	321.0341	-0.0041
	Jan. 28,1947	28,250	321.0357	321.0357	-0.0016
KN-PH	Dec. 11, 1946	12,000	139.0563	139.0563	
	Jan. 15, 1947	3,600	139.0595		
		4,100	139.0577		
		5,700	139.0546	139.0573	-0.0010
KN-WD	Feb. 8, 1947	4,100	181.0109	181.0109	
	Feb. 18,1947	7,000	181.0127		
		8,400	181.0064	181.0096	+0.0013
Average difference between means of sets of measurements of the same line made on different days					0.0014

lation in eastern United States. It is shown that no section of this triangulation in the general adjustment required a correction greater than one part in 66,000; and that 43 out of 55 had a closure better than one part in 100,000. It is not possible that the Coast and Geodetic Survey triangulation has a scale error of 1:20,000 as a whole.

Concerning the third source of error the whole mathematical procedure of velocity corrections and geometrical corrections was independently investigated by KROLL [1949] who integrated the basic differential equation of terrestrial refraction along the ray path, thus obtaining both the velocity corrections and the geometrical corrections simultaneously by methods which were mathemati-

Table 4--Shoran distances based on Anderson's velocity (299,776) compared with geodetic distances

Line	Geodetic distance	Reduced shoran distance	Difference[a]	Difference divided by geodetic distance
	mi	mi	mi	
1	101.9344	101.9265	-0.0079	0.000078
2	139.0629	139.0570	-0.0059	0.000042
3	143.5987	143.5911	-0.0076	0.000053
4	208.7428	208.7316	-0.0112	0.000054
5	227.1442	227.1330	-0.0112	0.000049
6	235.6710	235.6584	-0.0126	0.000053
		Mean	-0.0094	0.000055

[a] Shoran distance minus geodetic distance

cally independent of those of the staff working on shoran and which led to sensibly different paths. Kroll's final reduced shoran values agreed within a few feet, however, with the values produced by the project formulas. Kroll further concluded from his analysis that no significant contribution to the error could arise from errors in the meteorological measurements.

Concerning the fourth cause of error it should be noted that the dielectric constant for air consists of two parts: first, that for dry air; and second, the contribution due to moisture. The contribution due to dry air is derived from the optical index of refraction, which is accurately fixed from astronomical refraction measurements. That for moist air is somewhat uncertain; but the correction required to bring the measured distances into conformity is far larger than the physical uncertainties.

Concerning cause (5) it will be noticed from Table 1 that, contrary to what might be expected, the intensity correction is not correlated with the distance. This is a consequence of the choice of position in the lobe pattern made in flying the shoran lines. It was generally true throughout the operation that the intensity was uncorrelated or very weakly correlated with the distance. The correlation was certainly not strong enough to make any apprciable contribution to the error.

Nevertheless, it should be admitted that the effect of an error in the signal-intensity correction upon the resulting velocity would be very considerable. A least-squares solution by Kroll shows that if the signal-intensity correction is set equal to zero, a velocity is obtained almost precisely equal to Anderson's velocity with no appreciable change of the probable error. On the other hand, a value of zero for the signal-intensity correction seems physically implausible. The value of 0.00001 mi per unit of intensity was obtained from 139 observations and has a probable error of one-tenth of itself. The intensity correction thus appears to be quite well established, but further study of this point is indicated.

We are thus left with (6), the velocity of propagation of electromagnetic waves in vacuo, as the most probable source of the discrepancy.

Derivation of velocity--In accordance with the above reasoning the writer employed the following method to ascertain a value of velocity which would remove the correlation of error with distance. Increments were deduced which, added to the Anderson value of 299,776 km/sec, furnished new velocities which would best fit the goedetic distances, according to the following relationship:

$$\Delta V = (\Delta S/S)\, V_I \qquad (6)$$

where ΔV is the velocity increment to be added to V_I (299,776 km/sec), ΔS = the difference between shoran and geodetic distances, as listed in Table 4, and S = the reduced shoran distance. The tabulation is shown in Table 5.

The derived velocity of 299,792.4 km/sec agreed closely with Essen's 299,793, Bergstrand's 299,796, and Jones and Cornford's 299,788, being almost the exact mean of the three values.

Discussion of this new value of velocity with officials of the Army Map Service revealed the fact that an independent investigation has been made in that office using a different method. In their investigation, the geodetic distances were held fixed and the remaining 41 lines of the shoran network

Table 5--Computation of velocity from geodetic distances

Line	Difference[a]	Correction ΔV	Corrected velocity $V_I + \Delta V$	Deviation from mean
	mi	km/sec	km/sec	km/sec
1	-0.0079	+23.2	299,799.2	+6.8
2	-0.0059	+12.7	299,788.7	-3.7
3	-0.0076	+15.8	299,791.8	-0.6
4	-0.0112	+16.1	299,792.1	-0.3
5	-0.0112	+14.8	299,790.8	-1.6
6	-0.0126	+16.0	299,792.0	-0.4
		Mean	299,792.4	

[a] From Table 4

(see Fig. 1) were adjusted. In the adjustment, in addition to the K term, an additional term was introduced to give a multiplier by which all lines would be changed in length. The Rice adaptation of the variation of coordinates method was used by Mary Jane Camplair of the Army Map Service in making this least-squares adjustment.

The velocity resulting from the Camplair adjustment was 299,792.3 km/sec and K was practically zero. This was considered as strong evidence that the error was systematic with distance, applied equally well in all parts of the network, and that there was no appreciable constant error. The distances resulting from applying the velocity of 299,792.3 km/sec to the six lines on which geodetic measurements were made are given in Table 6, together with new comparisons with the geodetic distances.

Table 6--Comparison of geodetic and corrected shoran distances

Line	Geodetic distance	Corrected shoran distance	Difference
	mi	mi	mi
1	101.9344	101.9320	-0.0024
2	139.0629	139.0646	+0.0017
3	143.5987	143.5989	+0.0002
4	208.7428	208.7429	+0.0001
5	227.1442	227.1453	+0.0011
6	235.6710	235.6712	+0.0002
	Mean with regard to sign		+0.00015
	Mean without regard to sign		0.00095

The corrections or so-called v's derived from the adjustment are listed in Table 7. Column 4 lists the v's when a velocity of 299,776 km/sec is used and column 5 lists the v's when 299,792.3 is used.

Discussion of shoran results--It may be noted in Table 7 that Lines 7, 29, 30, 39, and 46 show very large decreases in the v's when the deduced velocity is used. Two lines (8 and 45) show moderate increases.

The probable error derived from the adjustment when using Anderson's velocity is ± 0.00402 statute miles and is reduced to ± 0.00355 when the adjustment is made with the deduced value of 299,792.3 km/sec.

Of a total of 47 lines, including the measurements over fixed lines, the ratio of the error (or the v) to distance on 43 lines is 1/25,000 or better. The remaining four lines, namely lines 28, 30, 37, and 43, have ratios of 1/14,300, 1/24,000, 1/18,100, and 1/20,800, respectively. The reason for the larger v's in the southwest part of the scheme may be due to the fact that the observational technique for observing signal intensity was not fully developed at the time those lines were flown.

It is also possible that somewhat of a "squeeze" occurred by holding all four Coast and Geodetic Survey stations fixed. As a test of shoran, it might have been somewhat better to apply the

Table 7--Corrections derived from the adjustment of 41 measured lines

Line	Designation	Approx. Length	Corrections in adjustments		Numerical changes in corrections
			V = 299,776	V = 299,792.3	
		mi	mi	mi	mi
7	TN-PN	336	+0.0077	+0.0012	-0.0065
8	TN-NL	340	-0.0024	-0.0059	+0.0035
9	TN-GN	229	-0.0009	-0.0019	+0.0010
10	WR-EW	102	+0.0008	+0.0010	+0.0002
11	WR-WD	163	-0.0037	-0.0032	-0.0005
12	WR-KN	186	+0.0041	+0.0033	-0.0008
13	WR-PH	112	-0.0034	-0.0024	-0.0010
14	EW-SL	148	+0.0020	+0.0017	-0.0003
15	EW-VG	344	-0.0014	-0.0017	+0.0003
16	EW-WD	108	-0.0007	-0.0001	-0.0006
17	EW-FN	304	-0.0001	-0.0001	0
18	EW-KN	230	+0.0014	+0.0016	+0.0002
19	EW-PH	206	-0.0008	-0.0014	+0.0006
20	SL-VG	225	+0.0014	+0.0013	-0.0001
21	SL-FN	246	-0.0003	-0.0007	+0.0004
22	SL-KN	278	+0.0020	+0.0030	+0.0010
23	SL-WD	99	-0.0032	-0.0038	+0.0006
24	VG-NL	367	-0.0016	-0.0027	+0.0011
25	VG-PN	279	+0.0020	+0.0021	+0.0001
26	VG-FN	148	+0.0002	+0.0013	+0.0011
27	VG-WD	241	-0.0003	-0.0002	-0.0001
28	NL-GN	113	+0.0090	+0.0079	-0.0011
29	NL-PH	331	+0.0060	+0.0024	-0.0036
30	NL-OS	123	-0.0127	-0.0051	-0.0076
31	NL-KN	215	-0.0012	-0.0003	-0.0009
32	NL-PN	97	+0.0016	+0.0016	0
33	NL-FN	226	+0.0049	+0.0035	-0.0014
34	GN-PH	243	+0.0072	+0.0060	-0.0012
35	GN-KN	163	-0.0006	-0.0007	+0.0001
36	GN-OS	67	+0.0001	+0.0020	+0.0019
37	GN-PN	145	-0.0068	-0.0080	+0.0012
38	PH-WD	227	-0.0040	-0.0063	+0.0023
39	PH-FN	321	+0.0085	+0.0045	-0.0040
40	WD-FN	199	-0.0054	-0.0053	-0.0001
41	WD-PN	271	-0.0014	-0.0023	+0.0009
42	WD-KN	181	+0.0053	+0.0072	+0.0019
43	FN-PN	133	-0.0060	-0.0064	+0.0004
44	FN-OS	209	-0.0055	-0.0032	-0.0023
45	FN-KN	190	+0.0010	+0.0048	+0.0038
46	PN-OS	102	-0.0066	-0.0006	-0.0060
47	PN-KN	151	+0.0037	+0.0058	+0.0021
	Probable error		±0.00402	±0.00355	

new velocity and adjust the shoran network as a whole, holding only one triangulation station and the azimuth to another. Nevertheless by the present criteria the shoran results appear to be excellent.

It is particularly noteworthy that the greatest reductions in the v's occurred in the two sliver triangles TN-PN-OS and PH-OS-NL.

Conclusions--The writer suggests that this approach to the determination of the velocity of propagation of radio waves may furnish a better value than the methods used heretofore. The method of determining velocity by shoran has certain advantages:

(1) The distances are so long that the limited errors of shoran do not cause large proportional errors. Where measurements are made at about the maximum shoran range the derived values of velocity acquire considerably more accuracy.

(2) The indicated precision of first-order triangulation is an excellent standard of comparison.

(3) The internal agreement of the shoran data is remarkably high and indicates an observational precision greater than the published results of the previous light-velocity measurements.

It is particularly important to note that triangulation of a very high order can be executed by shoran. The geodesist has a new tool at his disposal by means of which control can be extended over large unsurveyed areas, inter-continental ties can be made, and isolated island groups connected. During the course of these surveys repeated comparisons of shoran measurements with distances determined by triangulation will be made. In this manner, data will continually be collected to corroborate or modify the value suggested in this paper for the velocity of propagation of radio waves. The importance of this by-product in future physical research should not be underestimated.

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It is unfortunate that lack of space prevents enlarging the above list, for final success was due to the loyalty and enthusiasm of the individual officers and enlisted men of the Seventh Geodetic Control Squadron, U. S. Army Air Forces.

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RESEARCH STATUS AND NEEDS IN MICROCLIMATOLOGY

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Abstract--Extensive microclimatological investigations, currently under way in the United States, are primarily concerned with the vertical structure of the layer of air near the ground. Optimum progress in microclimatology is contingent upon improvement of measurements, articles and monographs synthesizing present knowledge, and standardization of terminology, techniques, and analyses.

Introduction--Study of the structure and physical characteristics of the layer of air immediately adjacent to the surface of the Earth has received greatly increased attention in the United States as an aftermath of the recent War, and has almost become a "fad" in some circles. This paper attempts to summarize the scope of such work for the benefit of other scientists to whom it is potentially of great interest and value. It also points out the great need in this field for improvement of measurements, for standardization of terminology, technique, and analyses, and for articles or monographs synthesizing present knowledge.

Definitions--"Microclimatology" and "micrometeorology" have been used somewhat interchangeably by students of the layer of air near the ground. "Micrometeorology deals with the physics of the layer and aims at discovering physical principles, whereas microclimatology is concerned with the geographical distribution both areally and vertically of the various properties of the air and seeks patterns of geographical distribution" [JOHNS HOPKINS UNIVERSITY, 1948]. While such a distinction may indeed be legitimate, it hinges upon the differentiation between meteorology and climatology, at best a moot question in professional circles, and one which is beyond the scope of the present discussion. Therefore, here, "microclimatology" shall be considered as all-inclusive.

However, the reference to the distribution both areally and vertically of the various properties of the air recognizes a terminology problem of some importance. Until recently, microclimatology was usually "the detailed study of the climate over a small area of the Earth's surface; for example, a single forest or even a cornfield" [THIESSEN, 1946], or distinguishing "between the climates of adjoining farms" with different slopes [BLAIR, 1942] and "over distances which, at most, amount to a few miles" [BRUNT, 1945]. The term has also been applied to "the study of the influence of cities upon air temperature, fog, sunshine, and the dust and smoke content of the air", [BLAIR, 1942], as well as "local effects of forests and small bodies of water" [BLAIR, 1942]. This study is more often called "local climatology" [L.C.W.B., 1945], and the urban aspect has been termed "climate made by man" [KRAUS, 1945]; GEIGER [1942] proposes "mesoclimatology".

The newer meaning of microclimatology as "the study of the typical climate of the lowest layer" of the atmosphere below the level of the usual "representative exposure" of meteorological instruments [HAURWITZ and AUSTIN, 1944], or of "the layering of the air" [CONRAD, 1944], has met with some objections [L.C.W.B., 1945; TOWNSHEND, 1948].

Etymologically, microclimatology can just as well apply to the large vertical variations and contrasts in conditions as to the horizontal ones. In the interest of clarity, however, it is desirable to subdivide microclimatology into these rather two distinct fields of interest. This was recognized by MATTHEWS [1937] when he found it useful to "divide microclimatology into two branches, in one of which the class of instrument and the technical skill required render untrained observation of little value, while in the other, by the use of quite cheap instruments, data of the utmost significance and interest may be secured, both by individuals and by group workers." These branches may be termed vertical and horizontal microclimatology. Thus:

Vertical microclimatology is the study of the vertical variations, in time and space, of conditions in the layer of air near the ground;

Horizontal microclimatology is the study of horizontal variations in time and space, of conditions from place to place, at distances up to a few kilometers, within the layer of air near the ground.

These may be considered as the studies of differences, respectively, between and along surfaces of air parallel to the Earth's surface. By far the largest activity in the United States in microclimatology today is in vertical microclimatology, and it is with this aspect that the remainder of this paper is principally concerned.

History--Until quite recently, American interest in the field of microclimatology was confined to a rather small group of enthusiasts who were, however, active pioneers. The extent to which they kept pace with the rest of the world is indicated in Table 1, a summary by decade and country of publication of microclimatic temperature studies cited in a recent bibliography [BAUM, 1948].

Table 1--Citation of microclimatic temperature studies

Region	1920-1929	1930-1939	1940-1947 (part)
Germany and Austria	29	49	11
America	13	10	10
England and India	12	10	4
Russia	6	10	0
All others	6	9	1

Even today, very few curricula of institutions of higher learning in the United States include courses in microclimatology, although such courses should prove of considerable benefit to students in such fields as ecology, agronomy, and engineering. In fact, as pointed out by LANDSBERG [1947], "there does not even exist an adequate modern text in the English language."

The only modern text [GEIGER,1942] is a monumental work. However, it is now seven years old, is highly descriptive, and goes into cumbersome detail on some points at the expense of over-simplification of others. Publication of an English translation of this work, with some subsequent revisions by the author, is contemplated by the Harvard University Press. The first edition (1927) of Geiger's book is available in an English translation by LEIGHLY [1942] for the Soil Conservation Service. An original American text is currently under preparation by Erwin R. Biel of Rutgers University.

In the Soviet Union a great deal of interest has been shown in microclimatology as a result of persistent efforts to increase land productivity. KOROTKEVICH [1936] published a text-like monograph on microclimatology which was essentially an abridged translation of Geiger's first edition. Few details on the present Soviet efforts are available, although microclimatological topics stand high on the list of research problems to be attacked under the current five-year plan [NIKANDROV, 1946].

Activity in the United States--In the United States, the increased interest in the field, confined to a limited number a few years ago, represents a dramatic development. Largely responsible is the strong influence exerted in the fields of meteorology and climatology by the armed services. A contributing factor has been the forward strides already achieved in instrumental techniques and apparatus.

The interest in microclimatology on the part of the armed services stems from such problems as turbulence, diffusion, and other factors; that is, primarily problems in vertical microclimatology. It remains to be hoped that the applicability and importance of microclimatology to ecology, land utilization and similar fields will not be slighted as a consequence of militarily-inspired research.

Currently there are in progress a number of primarily vertical microclimatological investigations, of which probably the largest in scope are those sponsored by the United States Air Force at Johns Hopkins University [HALSTEAD, 1948] and by the Office of Naval Research at the University of Texas [JEHN, 1948; GERHARDT and GORDON, 1948], and the research at Brookhaven National Laboratory [LUDLUM, 1948].

Work also is being or has been done by or through such agencies as the Chemical Corps and the Quartermaster Corps of the United States Army, by the Department of Meteorology and Climatology at the University of Washington, by the Department of Meteorology at the University of Wisconsin, by the Climatology Subsection of the Department of Agronomy at Iowa State College, by the Argonne National Laboratories in Chicago, by the Department of Engineering at the University of California at Los Angeles, by the Department of Physics at Pennsylvania State College [SCHILLING and Others, 1946], by the Daniel Guggenheim Airship Institute in Akron, by the United States Naval Ordnance Test Station in Inyokern [WILLIAMS, 1948] and by the Hanford Engineer Works in Richland, Washington [CHURCH and GOSLINE, 1948].

Thus large amounts of time and equipment and hundreds of thousands of dollars are currently being spent in microclimatological work. This offers a golden opportunity for development, an opportunity which must be exploited to the fullest to reap all the potential benefits. Unfortunately, despite the Symposium on Micrometeorology [GERHARDT, 1948] held in March 1948 at Austin, Texas, and a successor in February 1949 at Los Angeles, there is a sad lack of integration of the projects now in progress and proposed.

Research needs--To date activity in microclimatology has been principally of the problem type, as outlined by VAN CLEEF [1944]; it has been concerned with specific problems, whether they be frosts in Wisconsin cranberry bogs or Washington apple orchards, methods of determining evaporation from soils, or the dispersion of lethal gases. However, "in order to be most useful in a collaborative study the climatologist must obtain more information than is now available on the climate of the layer of the atmosphere next to the ground; he must know how temperature, moisture, and wind vary with height above the ground, within the cover of vegetation and immediately above it, and he must be able to say how the vertical gradients of temperature, moisture, and wind vary through the day and from season to season" [THORNTHWAITE and LEIGHLY, 1943]. The point has been reached where microclimatology must attempt to provide "a general meso- and microclimatological survey of our entire country against which the other natural sciences, both pure and applied, can compare the results of their own surveys and observations" [PARR, 1945].

Even the physics of the microclimatic layer is far from complete. As for all microclimatic elements, "to obtain a precise law of vertical wind distribution in the layer near the ground it is necessary to have observations taken throughout the day and at various seasons of the year, providing accurate measurements at various velocities, during different conditions of atmospheric stability and over different kinds of surfaces" [THORNTHWAITE, 1943]. Lack of observational material throughout the year, under all weather conditions, is largely responsible for the present limitations on knowledge. Many new phenomena undoubtedly remain yet to be discovered, and then explained, because of this absence of observational material. With the relatively vast facilities now available, even though much refinement of instrumentation remains to be done, for the first time there is promise of year-round, all-weather microclimatic data.

However, the mere taking of continuous microclimatic observations of greatly increased accuracy will not be sufficient. The data from different locations must be strictly comparable; observational standards must be established.

Historically, meteorologists came to an early recognition of the fact that the microclimatic layer is one of sharp contrasts with tremendous horizontal and vertical gradients of the various meteorological quantities. From the point of view of synoptic meteorology, primarily interested in obtaining observations representative of large areas, it was desirable to avoid this layer of disturbance. Consequently regular meteorological and climatological observations are taken at higher elevations in accordance with more or less definite standards agreed to by the meteorological services of the various nations.

No standard procedures, comparable to those existing for regular observations, are generally followed for microclimatological observations. From the point of view of synoptic meteorology it may not be deemed important whether the thermometer is located at a height of five or six feet. But for vertical microclimatic measurements below the level of standard meteorological observations, every inch is of the utmost significance. Consequently, until the undoubtedly complex laws governing the structure of the lowest air layer are established in precise form, it remains practically impossible to compare the results of different investigators in anything but the crudest, most qualitative fashion. Our understanding of the layer of air near the ground would be considerably greater had there been a certain amount of coordination and cooperation.

Various investigators in vertical microclimatology will prefer different levels for thermometers (or for instruments measuring other quantities) as a result of their particular interest. But it should be possible, without interfering with any of these special interests, to agree upon a certain number of standard levels at which observations are to be taken in all cases. This will not preclude the taking of observations at different levels for special purposes.

Such agreement would help to insure comparability, without hit-or-miss interpolation or impossible extrapolation, of data from various geographical and climatological conditions, prior to the establishment of the precise physical laws and would assist in the induction of these laws. Standardization need not await consideration by the International Meteorological Organization; the amount of observational work being carried on and planned in this country requires immediate action. The need for such cooperation cannot be overemphasized, and should be evident from those limitations imposed on past and present studies due to the lack of standardization on heights.

Standardization also is required on elements measured. To complete even the description of vertical temperature conditions, many further observations are required [BAUM, 1949]. Knowledge on the moisture distribution in the microclimatic layer is still more meager than that on temperature; as moisture is a very important factor in biological processes, atmospheric stability, and radiation balance, further data are indispensable. Wind structure, too, warrants much further investigation [THORNTHWAITE, 1949]; here there is the great advantage of some theoretical foundation to serve as a guide.

In addition to the vertical distribution of meteorological elements, simultaneous measurements are required of those other quantities included in the heat balance of the Earth's surface. These include: (1) temperature gradient in the soil, (2) soil conductivity, as a variable quantity, (3) insolation, direct and diffuse, (4) atmospheric radiation, (5) terrestrial radiation, (6) eddy conductivity in the air, and (7) evaporation.

These are general statements of the observational needs. They cannot be specific, because no one has compiled all the data which have already been taken. Almost as important as the need for standardizing the levels of observation and the elements to be measured is the demand for monographs on the present state of knowledge. Of over 800 papers on microclimatic observations [BAUM, 1948], not one is a synthesis of all available information, evaluating the efforts of various investigators and developing fundamental principles. Many papers, of course, refer to previous similar studies, but few cover the field fully and all are primarily concerned with their own data. Recently RAMDAS [1948] presented an excellent presidential address surveying microclimatology; 78 of his 80 references were to work done in India.

Such monographs would not only provide a new starting point for the much-needed future investigations, but would serve to apprise other scientists of the available information. Today, the entomologist or engineer interested in wind structure or temperature variation in the microclimatic layer must start from scratch and read through all the literature.

It may be that this need will be met somewhat by the Compendium of Meteorology, currently being prepared by the American Meteorological Society for the United States Air Force, which will present a survey of meteorological knowledge and of the major unsolved problems.

Research problems--But the mere taking of data, no matter how adequately, and its description, no matter how thorough, are not all there is to a science. Explanation is of the essence, and it is here that microclimatology and meteorology are most intimately tied together. Indeed, it is surprising that meteorologists have not been more interested in microclimatic problems.

A very basic problem in meteorology is that of the heat balance at the surface of the Earth. The atmosphere is heated and cooled primarily from below, yet we know very few details about the mechanism of heat exchange between Earth and atmosphere. Only when this problem has been solved will the observed extreme lapse rates in the microclimatic layer be explained and the influence upon the lapse rate of each of the various contributing factors understood.

This problem is complicated and requires a great deal of observational equipment and data. But as long as we are building steel towers, using complicated electrical equipment for the determination of meteorological quantities, and spending many man-hours, we might as well do the work properly even if some additional effort is required.

Only with complete observational material, as indicated above, under various weather conditions, can the instantaneous heat balance at the surface of the Earth be determined and related to the simultaneously existing lapse rate.

A variety of other microclimatic problems should be of direct interest to the meteorologist. A primary theoretical problem far from any satisfactory solution is that of the persistent daytime stratification in the very lowest air layers such that the density increases with elevation.

Another problem which may be cited is that of the time lag between noon and maximum temperature, a problem which provides a possible approach to the existence and extent of a laminar layer. The maximum temperature is attained when the net heat gain is zero, just as the heat loss begins to exceed the gain, not necessarily when the gross heat gain is at a maximum. Available observations indicate that this occurs at the surface of the Earth shortly after noon. A few centimeters up, however, an appreciable time lag is noted. This may be due to the fact that the surface's gross heat loss is increased by downward conduction to lower soil layers, no comparable source of heat loss existing in the atmosphere. On the other hand, it is possible and probable that there exists a thin layer of air through which heat is transmitted primarily through conduction, a slow process of heat transfer in the case of air. If this is the case, it may be possible to compute the depth of the laminar layer by obtaining the time-temperature curve at various heights and assuming that conduction only is responsible for the time lag. From the time lag, the depth of the conducting layer may be ascertained.

There is, of course, also a close causal relation between microclimatic conditions and evaporation and low-level turbulence. A better understanding of these processes and microclimatic conditions go hand in hand.

After measurement, description, and explanation comes application. This is in many respects the most important phase and is the one in which the meteorologist-climatologist primarily furnishes assistance to specialists in other fields. The potential utility of microclimatological results runs the whole gamut from land utilization to chemical warfare, including such diverse items as equipment specifications and insect control. Particularly in the field of agriculture, where scientific crop production becomes more essential as the world's needs continue ot mount, there has been an increased awareness of the need for application of microclimatological information. [THORNTHWAITE, 1948].

Conclusion--Instrumental difficulties are largely responsible for the fact that neither the purely descriptive aspect nor the physical cause-and-effect explanatory aspect of microclimatology has reached a stage sufficiently well advanced to permit accurate solutions to a number of practical problems. Some of these difficulties have been and are being alleviated by recent strides in instrumentation. Most of the material published as results of the projects now in progress has been concerned with instrumentation problems. While much instrumentation work remains to be accomplished, systematization of observations has now become a foremost problem.

Basic advances in microclimatology can come only when extensive, accurate, and systematic observations, under a variety of geographical and atmospheric conditions, are available. The generalization of such observations to new areas will then require a thorough understanding of various physical, biological, and geographic factors. And such understanding can be based only on systematic observations, made according to uniform procedures and at identical heights, standardized by agreement.

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PRELIMINARY REPORT ON MAGNETIC ANOMALIES BETWEEN ADAK, ALASKA, AND KWAJALEIN, MARSHALL ISLANDS

L. R. Alldredge and Fred Keller, Jr.

(Published by permission of the Office of Public Relations, Department of the Navy, and the Director, U. S. Geological Survey)

Abstract--A continuous record of variations of the total magnetic field intensity was taken along a single flight line from Adak, Alaska to Kwajalein, Marshall Islands, on Project Volcano during the summer of 1947. Anomalies as large as 750 gamma extending over distances of 20 to 30 mi were found over open ocean areas between Adak and Midway, where ocean depths range from 2000 to 3000 fathoms. A rather complete survey, at an altitude of 1500 ft above sea level, was made over Bikini Atoll and the adjacent seamount. A broad negative anomaly of 750 gammas was recorded over Bikini, with several superimposed more localized anomalies; those associated with the adjacent seamount were larger than those associated with Bikini.

Introduction--During June, July, and August of 1947, the Office of Naval Research, the United States Geological Survey, the Naval Ordnance Laboratory, and the United States Naval Air Modification Unit at Johnsville, Pennsylvania, cooperated on a large-scale magnetic survey in the Aleutian and Marshall Islands. The main purposes of the project were to map the total magnetic field intensity anomalies associated with several Aleutian Island volcanoes, the Aleutian Trench, and two atolls in the Marshall Islands. In completing this project approximately 31,000 mi were flown in a PBY-5A amphibious aircraft equipped with a total field magnetometer. Figure 1 indicates the flights made.

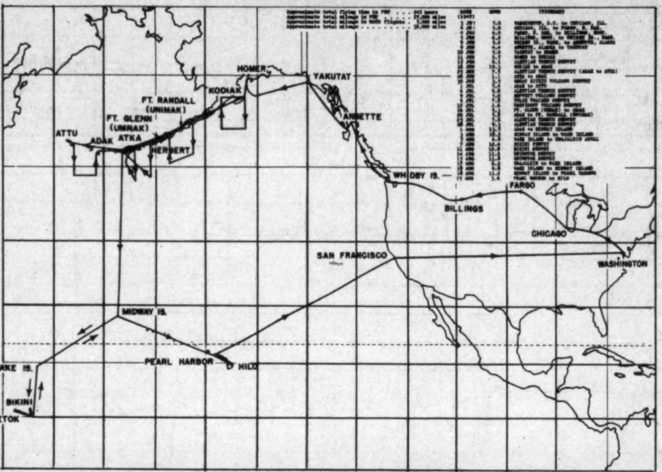
As a part of the survey, a continuous magnetometer record was obtained from Adak, Alaska to Kwajalein, Marshall Islands, via Midway and Wake Islands. This paper presents, in addition to this long flight-line data, the data obtained on a detailed survey made over Bikini Atoll and its nearby seamount. The remainder of the data taken in the Aleutian Islands on this project is the subject of a separate paper now in preparation.

Instrumentation--The survey aircraft was equipped with an orienting total field magnetometer developed by the Naval Ordnance Laboratory and the Bell Telephone Laboratories during the War. [FELCH and Others, 1947]. The magnetometer sensitive unit was housed in a fixed tail cone extending about four feet aft of the trailing edge of the rudder.

The magnetometer sensitive unit utilizes permalloy cores which are driven into saturation with a 1000 cycle per second driving current. The second harmonic voltage induced in the coil is proportional to the magnetic field along the core axis. The sensitive unit consists of three such elements mounted mutually perpendicularly in a gimbal mechanism. Two of these elements are used as orientators to keep the third element, called the detector, in line with the magnetic field vector. The magnetometer measures changes in the total magnetic field about an undetermined zero line. The zero line is steady with time except for a slow drift which depends upon the temperature and gradual decay of a battery which partially nulls the magnetic field to be measured. The intensity observed is automatically charted by a recording nulliammeter.

The magnetometer is capable of measuring changes as small as one gamma in the magnetic field while airborne. During this survey, however, the anomalies encountered were so large that a reduced sensitivity was required. The sensitivity used was such that a change of 500 gammas would produce a full-scale deflection of the recording meter.

In precise surveys such as the one over Bikini Atoll a base line is crossed every 15 min or less in order to permit correction for drift errors. On long flight lines a base line cannot be periodically crossed and therefore the drift error cannot be removed. The drift errors due to all causes probably average less than five gammas per hour and will not constitute a greater error than the diurnal variations, which have not been removed from the magnetic data taken along the flight line from Adak to Kwajalein. During the long ocean flights the position of the aircraft was not accurately known.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CHICAGO
SAN FRANCISCO
WASHINGTON
MIDWAY IS.
PEARL HARBOR
HILO
WAKE IS.
BIKINI
ENIWETOK

Fig. 1--Flights made on Project Volcano, June-September, 1947

Navigation was accomplished mainly by dead reckoning with occasional astro-fixes and very infrequent LORAN fixes. It is estimated however that the maximum error in the horizontal position did not exceed 25 nautical miles. Near the terminal points of each flight the position accuracy was much better.

Comparison of survey data with magnetic charts from Adak to Kwajalein--The total magnetic field intensity recorded along the flight path from Adak to Kwajalein is shown in Figure 2. The broken line represents data taken from the 1947 U. S. Hydrographic Office Chart No. 1703 of the Earth's total magnetic field intensity. The zero line of the data taken on this survey has been arbitrarily adjusted to provide good average agreement with the hydrographic chart data in the area between Wake and Midway Islands.

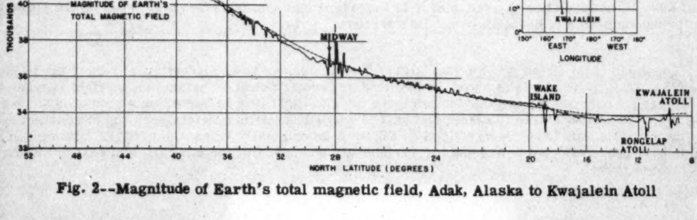

Fig. 2--Magnitude of Earth's total magnetic field, Adak, Alaska to Kwajalein Atoll

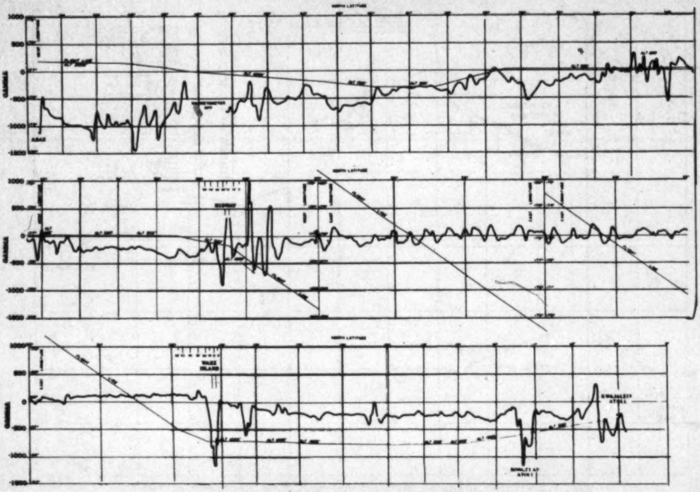

Fig. 3--Total intensity of magnetic field along anomaly flight line

A comparison between the broken line and an imaginary smooth line representing the solid curve of Figure 2 with local anomalies removed, indicates a discrepancy between these two sets of data. The discrepancy is as large as 400 gammas in the region extending south of Wake Island. As the curves were arbitrarily adjusted to match roughly between Wake and Midway, a different adjustment might introduce this discrepancy at other points along the curve. There is an uncertainty, however, in the continuity of the solid line through Midway, as the magnetometer nulling current was readjusted between landing and takeoff. It is nevertheless clear that a vertical readjustment of the the solid curve from Adak to Midway would still leave discrepancies of ± 500 gammas between the smoothed experimental data and the hydrographic chart data. That such a discrepancy exists is not surprising as this flight line is over an area where very few measurements [VESTINE and Others, 1947] are available to aid in the construction of the magnetic charts.

No extensive magnetic measurements have been made over open sea areas since the nonmagnetic ship Carnegie was lost in 1929. Considering the paucity of data available for use in construction of the magnetic charts in this region, and in view of the excellent performance and low drift rate of the airborne magnetometer, it is likely that the discrepancy between the magnetic chart data and data obtained on this survey indicates regional errors in the magnetic charts.

The ease and speed with which airborne measurements can be made indicate the importance of using this method to obtain data for world-wide magnetic charts. The ideal magnetometer for such a survey would, of course, be one which is capable of measuring all components while airborne. Until such instrumentation is available, it is important that nonmagnetic ships, such as the Research now being completed in England, be put into service.

Local anomalies from Adak to Kwajalein--The anomalous total magnetic field along the flight line from Adak to Kwajalein is shown in Figure 3 in greater detail. The anomalous field is taken as the difference between the two curves in Figure 2. The flight line is plotted on a grid of latitude and longitude. As the abscissae (distance on chart of recording milliammeter operating at constant speed) for the magnetic data have been retained in Figure 3 as originally taken, the grids of latitude and longitude have been distorted to account for variable ground speed of the aircraft, and changes in the direction of travel.

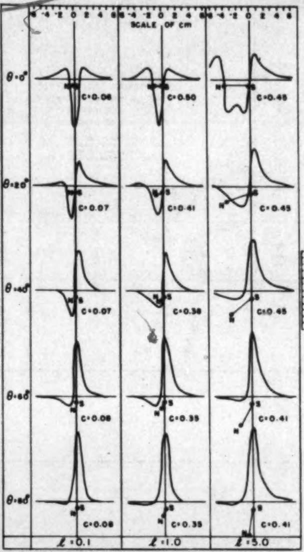

Fig. 4--Field component parallel to axis of magnet of a bar magnet NS of unit pole-strength for various values of length ℓ and inclination θ, South Pole S at depth $d = 1$, values shown to be multiplied by constant C (positive direction of field is from S to N)

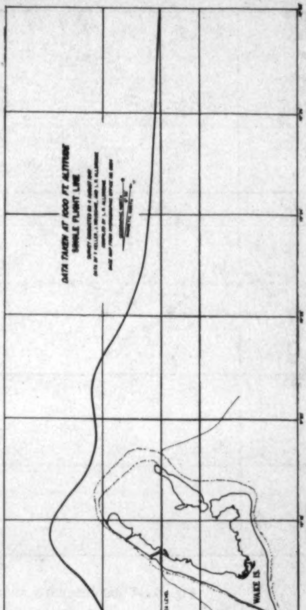

Fig. 5--Total intensity anomaly of magnetic field over Wake Island

Unfortunately the paucity of ocean-depth data makes it impossible to make a detailed correlation study between the ocean depths and the observed magnetic anomalies. In every case however, magnetic anomalies were observed over known shallow areas. The most striking examples of this are the anomalies over Midway, Wake, Rongelap, and Kwajalien.

The general shape of many of the local anomalies is such as to suggest ridges or seamounts in the basalt layer. The anomalies caused by the existence of magnetic material polarized by the present magnetic field of the Earth can be approximated by the field of magnets whose axes lie in the direction of the Earth's field. Figure 4 shows magnets of different lengths tilted at various angles. These tilt angles correspond to the magnetic dip (inclination) of the Earth's field for different latitudes, and the magnets represent the induced magnetism in anomalous basement structures. The different lengths ℓ (in cm) represent approximations differing from a simple dipole. In all cases the depth of the south pole S is taken as one centimeter and all pole strengths are taken as unity. In attempting to compare the magnitude of curves in Figure 4 with actual data it would be necessary first to adjust the pole strengths and depths to correspond to the anomalies themselves.

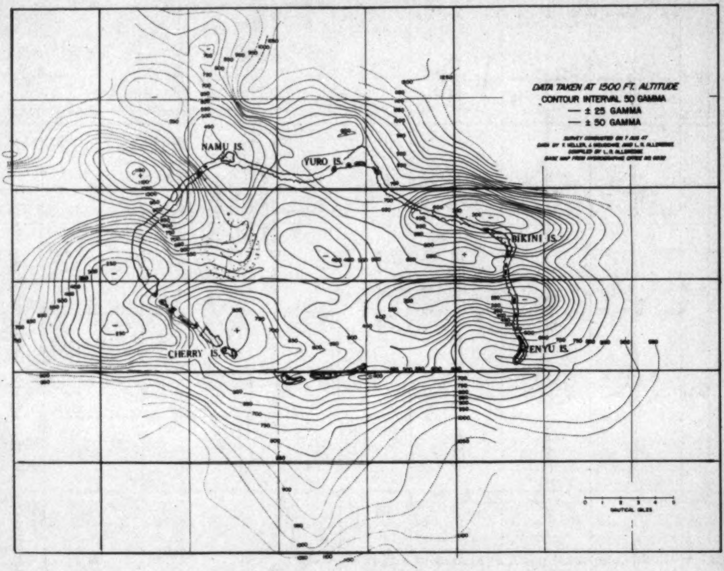

Fig. 6--Total intensity anomaly contour map of Bikini Atoll

Such adjustments are not necessary if only the shape of the curves are to be compared. The graphs show the component of the anomalous field parallel to the inducing field as a function of horizontal north-south distance from the shallowest pole of the anomaly. Only this component is of interest here, as in all observations during these surveys the anomalous field intensity was small compared to the ambient field of the Earth. Under these conditions only the component of the anomaly field parallel to the Earth's ambient field causes an appreciable effect on the total field magnetometer. These graphs are based on earlier work by VESTINE and DAVIDS [1945] . In general, viewing the flight path from left to right in Figure 3 corresponds to crossing anomalies from left to right in Figure 4.

According to Figure 4, anomalies at high latitudes with a simple geometric shape which can be approximated by a simple magnet, should exhibit single positive peaks with slight negative minima on the edges. As the dip angle decreases the small northern negative minimum grows larger at the expense of the main positive peak until at zero dip angle only a centrally located negative minimum remains with small symmetrical positive peaks at each edge. If the anomaly is extended in length, there may be a double minimum as shown in Figure 4 where inclination $\theta = 0$ and the magnet length $\ell = 5.0$.

Anomalies that are fairly well isolated in Figure 3 show that this general pattern is followed roughly. Anomalies such as those associated with Wake, Rongelap, and Kwajalein in low latitudes have a large central negative minimum, whereas those farther north exhibit a negative minimum to the north and a positive peak to the south.

The isolated anomaly between 15° and 16° N lat. is rather unique in appearance. The fringes indicate the presence of an excess of magnetic material polarized in the same direction as its neighbors, but the sudden positive peak at the center might indicate a region of reverse polarization or a large cavity or mass of non-ferromagnetic material at the center.

One of the most interesting aspects of the flight line from Adak to Midway is the large number of local anomalies observed over regions of the ocean shown on hydrographic charts to be approximately 3000 fathoms deep. Typical of these are the irregularities shown near 33°, 34°, 38°, 45°, 48°, and 49° N.

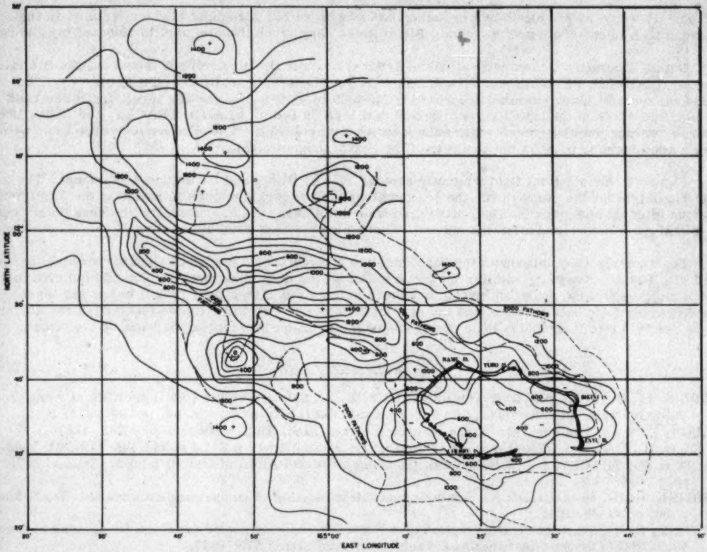

Fig. 7--Total intensity anomaly contour map of Bikini Atoll and adjacent seamount

Pogy and Nero banks, which rise to within 50 fathoms of the surface, are indicated by the very large anomaly starting approximately 30 mi southeast from Midway and extending nearly 60 mi. The amplitude of the anomaly shown near Midway is not accurate as the altitude was not held constant. The magnetometer was operated as the aircraft let down for a landing from the north and was turned on again soon after taking off 24 hours later while gaining altitude flying in a southeastern direction. The data very near Kwajalein Atoll are of questionable accuracy for the same reason.

An accurate continuous profile was obtained over Wake Island by flying north after the takeoff to gain the proper altitude, then heading south for Kwajalein. A detailed large-scale plot showing this profile over Wake Island is shown in Figure 5. The magnetic anomaly is shown by the heavy line with negative values plotted upward. The ocean depth is shown by the broken line. Unfortunately, the depth data are not known in detail from 600 fathoms down to the 3000 fathom general bottom depth in this area, but from the appearance of the anomaly Wake Island might have been built on a very broad (approximately 30 mi wide) basement seamount.

Over 100 seamounts [HESS, 1946] have been discovered in the area between the Hawaiian Islands and the Marianas. Most of these seamounts are very flat topped and rise to within 500 to 800 fathoms of the surface, and are from ten to 20 mi wide. One of these seamounts approximately 50 mi northwest of Bikini Atoll produced an anomaly very similar to the anomalies produced by Bikini, Wake, and Rongelap. It is likely that the substructure supporting the seamounts and the South Pacific atolls are similar in nature. The negative anomaly just north of 18° N. (see Figure 3) could well indicate another uncharted seamount.

Survey over Bikini and adjacent seamount--A detailed survey was made over Bikini and the seamount 50 mi to the northwest. Eleven north-south and eight east-west survey lines, spaced two miles apart were flown across Bikini Atoll. Most of the lines were continued approximately ten miles seaward beyond the coral reefs. Figure 6 shows the resulting detailed contour map. A few minor positive peaks are seen to occur within a broad negative anomaly of approximately 750 gammas. This type of anomaly would be produced by a broad seamount with rather irregular surface features in the basement. A north-south profile across Bikini looks very much like the profile obtained over Wake.

During Operation Crossroads at Bikini several seismic profiles were obtained across Bikini Lagoon [DOBRIN, PERKINS, and SNAVELY, 1949]. These indicated three distinct layers. The top of the deepest layer extended downward from 7000 to 13,000 ft below sea level, and it has been assumed that this is the basalt layer. Recent drillings on Bikini [LADD, TRACEY, and LILL, 1948] indicate nothing but calcareous sediments down as far as 2500 ft. These seismic profile lines will give a good starting point in the analysis of the Bikini magnetic data.

Figure 7 shows a total field magnetic contour map of Bikini and its adjacent seamount. The ground control for the survey over the seamount was not accurate enough to maintain the 50 gamma contour interval of Figure 6. The entire area was flown using dead reckoning with check points taken on Bikini Atoll before and after the survey. These check points were approximately eight hours apart.

The anomaly associated with the seamount has a larger peak amplitude than the anomaly associated with Bikini. Assuming similar magnetic material for both structures, this would indicate that the basalt peaks of the seamount probably rise to heights much less than 7000 ft below sea level. Since hydrographic data indicate that the seamount comes within 680 fathoms (4080 ft) of the surface of the ocean, there is probably little if any nonmagnetic material capping the basaltic seamount.

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THE MEASUREMENT OF WAVE HEIGHTS BY MEANS OF A FLOAT IN AN OPEN-END PIPE

J. D. Isaacs and R. L. Wiegel

Abstract--A series of experiments was performed to test the possibility of using open-end pipes with float-type recorders for measuring wave heights, for the purpose of applying these data to the planning of coastal engineering structures. The main problem was one of resonance in the tubes. This was particularly pronounced in actual installation for wave periods of from one to six seconds. A mathematical analysis has been made for the case of a train of waves of constant period. It was shown that the band of frequencies encountered in the ocean would make it quite difficult if not a practical impossibility to analyze data obtained by this method.

Introduction

In the construction of piers, jetties, dams, sea walls, and other structures in contact with large bodies of water, it has been found necessary to have some knowledge of the height and period of surface gravity waves (swell and breakers) that would act upon them. The observations of local inhabitants have often proved to be erroneous, and as a consequence it has been found necessary to assemble a statistical group of data from actual wave measurements. One of the possible methods of measurement would be the use of a recording device coupled to a float in an open-end tube extending to some depth below the water surface.

Vertical pipes immersed in the ocean have frequently been used to measure tidal variations. These pipes, installed from piers or jetties, normally have been damped to such an extent that no fluctuations have been recorded except the long period surges and tide changes. Such data have proven quite dependable. In order to use such a pipe for the measurement of relatively short-period storm waves, the damping effect would have to be removed. Because it was believed that a resonance condition would exist for these short periods, an experimental study was conducted to determine the details of the phenomenon.

Theory--Consider an open-end pipe, of cross sectional area S, immersed to some depth ℓ in a very large body of water with a series of oscillatory waves (period = T_w) going by. At the bottom of the pipe there will be some pressure due to the wave. Calling this H_ℓ (in feet of water), and assuming Z small compared to ℓ, we have as the equation of motion (see Fig. 1)

$$(\ell Sw/g)\, d^2Z_1/dt^2 + C dZ_1/dt + wSZ_1 = H_\ell\, Sw\, (\sin \omega t)/2$$

where

$$\omega = 2\pi/T_w$$

$$d^2Z_1/dt^2 + (Cg/wS\ell)\, dZ_1/dt + gZ_1/\ell = H_\ell\, g(\sin \omega t)/2\ell \ldots\ldots\ldots\ldots (1)$$

This, being a second order linear differential equation with constant coefficients (the forced vibration equation), has the solution of (letting $C' = Cg/wA\ell$)

$$Z_1 = A \sin(\omega t - \alpha) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where

$$A = H_\ell \Big/ \left\{ 2\sqrt{[1 - (T_n/T_w)^2]^2 + (C'\ell/gT_w)^2} \right\}$$

and

$$\alpha = \tan^{-1} \left\{ C'\ell/T_w g\, [1 - (T_n/T_w)^2] \right\}$$

The natural period of the pipe was found from an intermediate step in the solution of (1), considering the general solution of the reduced equation (that is, the free or natural oscillation part)

$$Z_1 = e^{\alpha t}(A \sin \beta t + B \cos \beta t) \quad \ldots\ldots (3)$$

where

$$\alpha = -Cg/2wS\ell$$

$$\beta = \sqrt{(g/\ell) - (Cg/2wS\ell)^2}$$

The period would be the time necessary to complete one cycle; that is

$$T\sqrt{(g/\ell) - (Cg/2wS\ell)^2} = 2\pi$$

or

$$T = 2\pi/\sqrt{(g/\ell) - (Cg/2wS\ell)^2} \quad \ldots\ldots (4)$$

and the natural, undamped period would be

$$T_n = 2\pi/\sqrt{g/\ell} = 2\pi\sqrt{\ell/g} \quad \ldots\ldots (5)$$

Experimental procedure

A one-inch open-end glass tube was immersed vertically in the wave channel (1 ft X 3 ft X 60 ft) in the Fluid Mechanics Laboratory at the University of California at Berkeley. Two immersed lengths were used; a 2.0 ft length with a natural period (T_n) of 1.64 sec and a 1.0 ft length with a natural period of 1.14 sec. The amplitude of oscillation of the column was measured when waves of various periods and heights were generated by a wave machine. The oscillation was allowed to reach a state of maximum response. Phase shift was estimated by measuring the distance to a crest at the time that the liquid column had reached a maximum or minimum. The natural period of the tube was determined by dispacing the water surface within the tube and timing a number of oscillations (see Fig. 2).

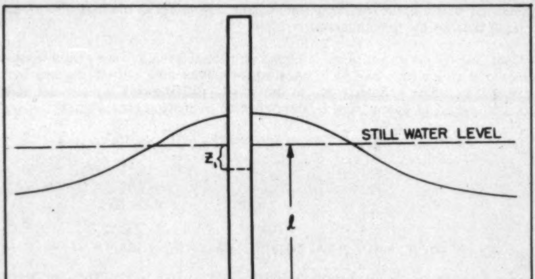

Fig. 1--Tube immersed in water with a wave impressed

Experimental results

Magnification factor--The response was much as expected. The amplitude showed a magnification factor of 10.8 for the one-foot tube and 12.2 for the two-foot tube at the resonant period (see Fig. 3 and 4). The magnification factor was computed in respect to the theoretical pressure variation at the bottom of the tube as given by the equation for subsurface pressures due to oscillatory gravity waves [FOLSOM, 1947]

$$H_Z/H_W = \cosh[2\pi(D - Z)/L]/\cosh(2\pi D/L) \quad \ldots\ldots (6)$$

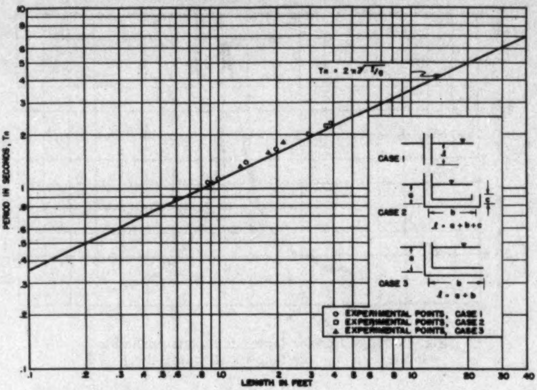

Fig. 2--Natural periods for different forms of immersed tubes

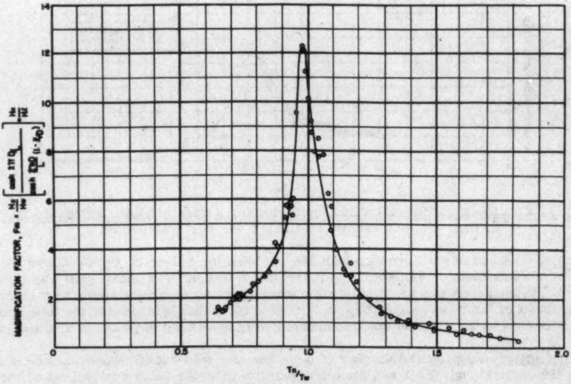

Fig. 3--Magnification factor for a one-inch tube immersed two feet below still water level

where D is the depth of the body of water, L the wave length, Z the depth of the tube, below still water level, H_W the height of the wave and H_Z the pressure at depth Z due to the wave of height H_W (in this case, $H_Z = H_\ell$ as $Z = \ell$). The apparent magnification factor was merely the ratio of the recorded height to the wave height (H_R/H_W) without considering the pressure attenuation. This factor reached a maximum of 4.4 for the one-foot pipe and 6.8 for the two-foot pipe at the resonant periods (see Fig. 5). The reason for the apparent undulations at values of T_n/T_W between 0.5 and 0.8 for the one-foot submergence was not fully investigated.

Damping--The coefficient of damping was about 0.08 for the two-foot immersed length and about 0.09 for the one-foot immersed length.

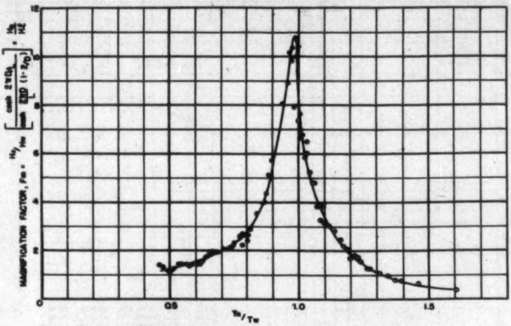

Fig. 4--Magnification factor for a one-inch tube immersed one foot below still water level

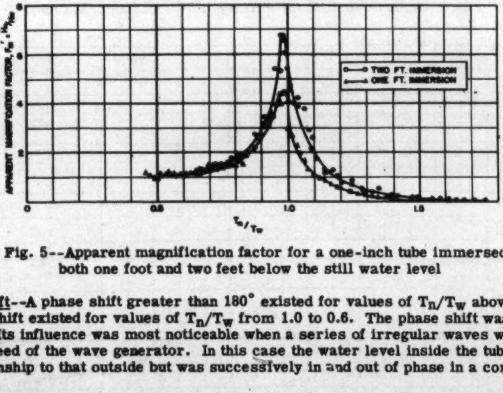

Fig. 5--Apparent magnification factor for a one-inch tube immersed both one foot and two feet below the still water level

Phase shift--A phase shift greater than 180° existed for values of T_n/T_w above the critical. A significant shift existed for values of T_n/T_w from 1.0 to 0.6. The phase shift was not completely investigated. Its influence was most noticeable when a series of irregular waves was produced by varying the speed of the wave generator. In this case the water level inside the tube showed no simple relationship to that outside but was successively in and out of phase in a complex manner.

Pumping action--In a limited number of tests the tube was cut off somewhat below the height reached by the oscillations. This resulted in a quantity of water being pumped out of the upper end of the tube to an elevation of several times the wave height above the mean surface. No quantitative data were taken on this phenomenon.

Application

In order to estimate the effect that this resonant condition would have in an actual installation, the response characteristics were applied directly to a typical pier installation. Two tide stages were chosen, MLLW and + 10.0 ft. Wave periods of from one to 15 sec were investigated. The conditions shown in Figure 6 were considered typical, bearing in mind the limitations presented by most piers. The coefficient of damping for prototype conditions was assumed to be the same as in the model. Actually, considering the diameter of pipes in use in such installations, the damping probably would be much less if a simple open-end pipe were used. Thus, the amplification factors would be greater. It can be seen by reference to Figure 6 that waves of periods from one to six seconds would result in an exaggerated response.

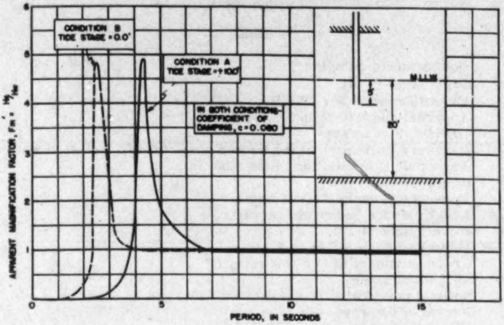

Fig. 6--Response characteristics for an actual installation

Assuming that this type of recorder would have certain attendant advantages, it is quite possible that some remedial alterations could be taken. It probable is that a satisfactory recorder could be designed if the open end were never more than five feet below the mean water surface. This would limit its use to recording waves under about 12 ft in height. This also would mean that considerable damping would have to be introduced as a response of five or more to waves of two to four-second periods would seem undesirable. If critical damping could be introduced on a pipe of an immersed length of five feet, waves of five- to six-second period and above probably could be recorded to an accuracy of ten per cent (reference condition B, Fig. 6). To accomplish this, the effect of tide stage on immersed length would, of course, have to be eliminated. Several possibilities present themselves: (a) The immersed pipe could be supported by floats acting in stilling wells, thus preserving the critical dimension. (b) The pipe might be perforated at intervals and the perforations covered by flap valves or by a gate which would be adjusted by a float acting in an adjacent stilling well. A float that is not in a pipe would be subjected to the effect of flotsam and horizontal currents. In this connection, the pipe could not have a submerged horizontal arm which would be raised or lowered by rotation at a joint, without again increasing the natural period of the pipe.

Discussion and conclusion

In the ocean, it would be rare that a series of waves of constant period would be traveling past an installation. Consequently, any calibration with respect to the wave period would be voided by the band of frequencies which are normally encountered in the ocean. The response to any train of short-period waves would be very complex. In addition, it should be noted that waves are trochoidal in shape and the pipe probably would respond to the short sinusoidal components of the Fourier series representing a long-period trochoidal wave. In this connection it should be remembered that the waves (which were trochoidal) studied in the channel were of relatively short period.

The pumping effect was interesting, and it would appear that a properly designed pipe could result in raising relatively large quantities of water to a height of 20 to 30 ft above the water surface when waves of four to five feet exist. For this purpose a vertical pipe would not be advantageous and one of the type shown in Case 2, Figure 2 should be employed.

Acknowledgments

The investigation described in this paper was conducted as part of an extensive study on waves sponsored by the Bureau of Ships and the Office of Naval Research.

APPENDIX 1

Notation

C	Coefficient of damping
D	Depth of water, ft
F_m	Magnification factor, H_R/H_ℓ
F_m'	Apparent magnification factor, H_R/H_w
g	Gravity, 32.2 ft/sec^2
H_ℓ	Pressure fluctuation at the bottom of the tube ($Z = \ell$), ft of water
H_R	Amplitude of oscillation in the tube, ft
H_w	Height of wave, ft
H_Z	Pressure at depth Z, ft of water
ℓ	Length of tube immersed in water, ft
L	Wave length, ft
MLLW	Mean lower low water, a datum
S	Cross-sectional area of the tube, ft^2
SWL	Still water level
$x\,T_n$	Natural period of oscillation of the tube, sec
T_w	Period of the wave, sec
w	Unit weight of sea water, 64 lb/ft^3
Z	Distance to any subsurface point from SWL, ft

Reference

FOLSOM, R. G., Subsurface pressures due to oscillatory waves, Trans. Amer. Geophys. Union, v. 28, pp. 875-881, 1947.

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STUDIES OF WAVES AND SWELL IN THE WESTERN NORTH ATLANTIC

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Abstract--Waves and swell have been recorded off western Cape Cod and eastern Bermuda by means of underwater wave meters. The waves and swell recorded off Cape Cod appear to fall into two groups having relatively short and long periods, respectively. The former group (5.5 to 11 sec) is correlated with prevailing southerly winds over east coastal waters. Study of the long-period swell suggests a more distant origin, with indications that ocean swell travels with constant period and group velocity. Some general rules relating to storm positions and observed swell are derived from the wave and weather data associated with two Atlantic storms.

Introduction

The purpose of this paper is to present a summary of a study of waves and swell recorded through instrumental means, and an interpretation of such features in terms of conditions of origin and propagation. The study has been concentrated on wave recordings made off southwestern Cape Cod, but some attention has been given certain related records made by instruments off eastern Bermuda. For purposes of discussion to follow, the observations have been arbitrarily classified into prevailing waves and swell, and storm swell.

The value of this and of future work appears to be several fold: An instrumental means is provided for studying the validity and further applications of the wave and swell forecast theory of SVERDRUP and MUNK [1947; also ARTHUR, 1948]; basic data for the design of coastal engineering structures can be furnished as has been demonstrated for the west coast by JOHNSON and ISAACS [1948]; MASON [1949] has stressed the value of ocean-wave knowledge in the study and remedy of beach-erosion conditions; the importance of application of wave and swell data to the problems of ship design has been stated by MASON [1949] and REVELLE [1948]; and the significance of swell "forerunners" has long been recognized in areas affected by tropical disturbances.

Instruments and data

The two principal sources of data for this study were Woods Hole Oceanographic Institution wave records and record analyses and synoptic weather charts of the North and South Atlantic.

Wave instruments and data--A full description of the Woods Hole wave equipment is given by KLEBBA [1949]. Since a consideration of the primary wave data is so integral a part of this presentation, a brief discussion of the nature of the instruments and the resulting data seems appropriate. The basic equipment consists of a wave meter and recorder and a harmonic analyzer. The meter is an underwater bottom-resting unit that responds to pressure changes induced by the passage of surface waves above. It is compensated for slow tidal effects. In response to these pressure changes the meter develops a varying electric signal which is transmitted by cable to a shore-based galvanometer type recorder. During the period of operation a continuous wave-profile record is made on a photographic tape or film on which timing marks are also impressed.

The photographic wave profile is analyzed for the component periods present by means of a frequency analyzer. The output of the analyzer is automatically plotted on a periodogram chart yielding a "spectrum" of periods present in the original wave record pattern. This analysis consists of some amplitude factor plotted against period. The wave spectrum is of particular value in distinguishing swell from different sources. In general, the spectra of greatest value are those in which distinct wave or swell groups can be recognized, or in which narrow bands of frequencies occur. Cumulative experience is of importance in interpreting the wave records and periodograms.

Although wave or swell period is a more conservative property than height, and is the basis for wave or swell identifications made in this study, height determinations are of distinct value. Unfortunately no specific quantitative amplitude values can be determined from the wave analyses. Such values must at present be determined from the measurements on the photographic wave profile as indicated by KLEBBA [1949]. A further limitation occurs here. Normally, the heights of waves or swell of relatively local origin are so much greater than those of more distant origin that they tend to mask the latter group. This permits height values to be determined only for waves or swell of close origin; exceptions exist when pronounced swell from distant severe storms shows on the records.

A distinct asset of this type of wave meter lies in the elimination from the recordings of short-period "chop" of very local wind origin. Hence the longer waves and swell which are of greater significance are easier to study. This occurs since the pressure fluctuation with depth varies with both depth of water and wave period in such a way that at a given depth the pressure change is greater for waves of longer periods. Curves are available which give the pressure fluctuations from surface waves as functions of depth and period.

Location of wave meters--Most of the wave data were obtained from the Cuttyhunk meter located about a mile southeast of Cuttyhunk Island, near the western end of Cape Cod, at a depth of 78 ft. Owing to the coastal configuration and the presence of shoals and islands to the east, the exposure of this instrument appears to limit the recording of waves and swell to those approaching from a sector between southeast and southwest. Wave data have also been obtained from a second meter located off eastern Bermuda, at 32° 20′ N, 64° 39′ W. This instrument is at a depth of 118 ft and is approximately south-southeast of the Cuttyhunk meter.

Synoptic weather charts--The weather charts employed in the study were essentially the six-hourly maps of the North Atlantic prepared by the Transatlantic Forecast Division of the United States Weather Bureau at La Guardia Field on Long Island. For the study of certain swell groups referred to later, maps of the South Atlantic were required. A sequence extending over a one-year period was generously provided by the Meteorological Office of the Union of South Africa.

In the preparation of trial wave and swell forecasts, geostrophic wind values were determined from the above charts by means of nomograms or graphs devised for three-millibar pressure differences and the appropriate map scale. These figures were then reduced to surface wind conditions and checked whenever possible by comparison with wind observations recorded on the synoptic charts.

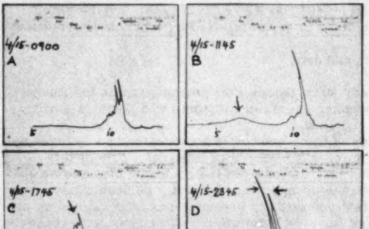

Fig. 1--Harmonic analyses of April wave records referred to in Table 1; this short-period sequence first appears on record B, above, and reaches a maximum period on record F (period is shown in seconds on the horizontal axis)

Prevailing waves and swell

Study of the wave recordings and spectra over a two-year period show that prevailing waves and swell can be separated into two groups having relatively long and short periods, respectively. The short-period group, when present, usually dominates the record owing to its greater height.

The short-period group--This group ranges in period from 5.5 to a maximum of 11 sec, with periods of from seven to ten seconds being most common. (The equipment does not respond to waves of lesser period although they are frequently present from local wind influences.) From the study thus far it appears that the short-period waves are most prominent during late spring, summer and early autumn.

Table 1 summarizes the data for three sets of short-period wave sequences in which the growth of the wave could be easily traced from nil to maximum period and height. These cases correspond exactly to intervals in which distinct southerly wind systems prevailed along east coastal waters. Consequently trial forecasts of wave height and period were made by means of the wave and swell forecast theory of SVERDRUP and MUNK [1947] referred to hereafter as the "forecast theory." These results are shown in the Table 1 for comparison of recorded and forecast values. The wind duration and average surface velocity are also given. A graphic picture of the growth of the April waves of Table 1 is shown on the wave spectra of Figure 1.

Table 1--Short-period waves

Date	EST	Recorded[a]		Forecast[b]		Surface wind	
		Period	Height	Period	Height	Duration	Aver. velocity
1946	h m	sec	ft	sec	ft	hr	knots
Apr. 15	07 30	not recorded		4.0	7.0	6	24
	13 30	5.7	9.6	6.5	18.5	12	35
	19 30	6.7	10.8	7.0	16.5	18	30
Apr. 16	01 30	8.2	9.3	7.9	18.0	24	31
	07 30	9.0	8.5	7.3	11.0	30	23
	10 30	9.8	7.7	7.5	11.0	33	22
May 11	07 30	5.6	2.2	3.9	7.0	6	23
	13 30	5.7	8.4	5.4	10.7	12	25
	19 30	6.3	12.0	6.2	11.1	18	24
May 12	01 30	6.8	12.1	6.9	12.0	24	24
	07 30	7.3	7.2	7.5	12.0	30	24
	13 30	7.9	8.7	8.0	12.1	36	24
	19 30	8.3	7.0	8.5	12.1	42	24
June 30	19 30	not recorded		3.0	3.5	6	15
July 1	13 30	5.0	3.6	5.8	7.5	24	17
	19 30	5.8	5.0	6.4	7.5	30	18
July 2	01 30	6.3	8.3	6.9	8.0	36	19
	07 30	6.8	9.8	7.3	8.1	42	19
	13 30	7.0	11.1	7.5	8.1	48 (44)[c]	18
	19 30	7.0	11.1	7.1	7.7	54 (44)	18
July 3	01 30	7.0	11.1	7.1	7.7	60 (44)	18

[a] Maximum height. [b] Average height of highest one third. [c] According to the fetch and wind velocity used the forecast theory indicates 44 hr to be the minimum duration, that is, the interval beyond which a steady state of height and period occurs.

Discussion--The April sequence of Table 1 shows better correlation of recorded-forecast periods than of heights, the latter showing discrepancies reaching 100 per cent. A disagreement in period occurs toward the end of the sequence with recorded periods increasing, although a decrease in wind velocity is shown. In order for the forecast period to show a similar increase, the maintenance of the higher velocity was required, but this would further increase the height discrepancies. In preparing wave forecasts for the East Coast, similar height errors were noted by EMMONS and CLARKE [1945], and STUMP [1944]. It should be pointed out, however, that the forecast procedure is a very subjective one.

For the May sequence the principal discrepancy between recorded and forecast values exists for the heights also. Although the synoptic charts indicated a uniformity of wind velocity during the interval, the recorded height decreased after 01^h30^m, May 12, while the period increased. The reason for this is not clear.

The constancy of period and height after 13^h30^m, July 2, indicates the apparent achievement of a steady state of wave features for the fetch and velocity of wind which prevailed off the coast.

Synoptic conditions causing generation of short-period group--Study of the wave records and associated marine weather charts shows that the short-period waves of this group are most prominent when generated by southerly winds off the East Coast. The atmospheric circulation is such that easterly winds in these latitudes are scarce and of short duration and fetch. It is coincidental that southerly winds often prevail in the "window" of approach to Cuttyhunk, referred to earlier. The prevalence of these winds during late spring, summer, and early autumn explains the prominence of this group during that period. The pressure patterns most likely to yield appropriate winds may be summarized as: (1) Large low-pressure area with center passing over New England or southern Canada and having a well-developed warm sector with straight isobars extending northward along coastal waters; (2) presence of a high-pressure area in Bermuda waters (transitory winter situation, but characteristic in summer); (3) a combination of situations (1) and (2); and (4) a low-pressure area moving northward along the coast - a situation more common during winter months.

Once familiarity is gained with the above conditions and related wave records, qualitative wave forecasts can be made in which period can be predicted with good accuracy. Height is a more variable property, being more sensitive to small or temporary wind changes.

In most of the cases studied, the wave generating period was closed by the passage of a cold front, often followed by strong west to northwest winds across coastal waters. Nevertheless, in many cases, including the April and May sequences in Table 1, the wave period persisted at a maximum for as long as 12 to 18 hr after the frontal passage. No quantitative studies of this have as yet been made, but it appears possible that this continuation was maintained by the strong west winds which followed the fronts. This would be in accordance with the wave direction variability theory of ARTHUR [1949].

In most cases, the fetch of the southerly winds responsible for the generation of the short-period group extended to, or nearly to, the recording station. Since swell consists of waves that have outrun or traveled away from the generating winds, the short-period group treated above may be considered as having more the characteristics of wind waves than of true swell.

Long-period swell--A distinct swell group with a mean period of about 15 sec occurs on nearly all the wave spectra. The periodograms frequently show a unique wave signature exactly at the 15-sec mark. This group may show a range of from 14 to 18 sec, with occasional extensions slightly beyond these limits. From a study of many records it appears that this group is nearly always present, but at times may become too small to be detected, even by harmonic analysis. This swell appears to have had a very distant origin involving long travel times, and long distances of decay from the generating area. The amplitudes of this group are usually too small to permit accurate determinations by measurement from the wave records. At times of greater prominence this group can be distinguished on the photographic wave record by its interference effect with the shorter higher waves.

From the Cuttyhunk exposure referred to previously, and also from the rarity of easterly winds in the North Atlantic, it has been assumed that this swell approaches from the south. A means of checking this assumption is provided by an examination of the records of the underwater wave meter located off eastern Bermuda. Spectra of the Bermuda records show the same long-period groups as appear on Cuttyhunk records. Further, the distance between the Bermuda and Cuttyhunk stations is 560 mi. Thus these stations are on a line with approaching southerly swell, and at a known separation. If a distinct frequency band can be identified on the Bermuda spectra, then by allowing appropriate travel time, the same pattern although with diminished amplitude should appear on the Cuttyhunk spectra.

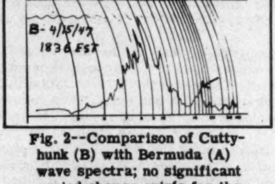

Fig. 2--Comparison of Cuttyhunk (B) with Bermuda (A) wave spectra; no significant period change exists for the swell whose signatures are indicated with arrows; the wavy lines at the top of the periodograms are tracings of the actual photographic wave records

This investigation has been made for many such cases which often show strikingly similar patterns on Bermuda and later Cuttyhunk

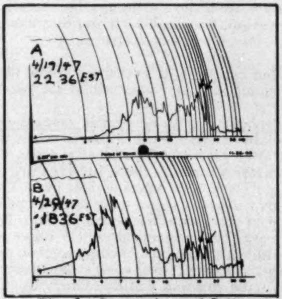

Fig. 3--Comparison of Cuttyhunk (B) with Bermuda (A) wave spectra; for explanation, see Fig. 2

periodograms. Figures 2 and 3 show examples, and compare Bermuda with Cuttyhunk records at as close to the appropriate time differences as the records permit.

Assuming this southerly origin, weather maps of the belt of the Westerlies of the Northern and Southern Hemispheres have been studied at length. No such swell source appears possible from transitory cyclones and anticyclones of either hemisphere. In addition the "window" of approach from possible storms in the South Atlantic is extremely restricted. The suggestion is thus offered here that this swell group is generated by the Southeast Trade Winds. This seems to be the only source that would explain their constancy. The shorter period swell of lesser energy, also generated by these winds, is probably damped before reaching higher northern latitudes. The prominence of this long swell group probable varies with the strength of the Southeast Trade Winds and with the strength of opposing winds over the area of travel.

Another indication of importance is suggested from a study of the Bermuda and Cuttyhunk records. Figure 2A shows the maximum long-period wave energy to be at 16.9 sec on the Bermuda record of 19^h14^m EST, April 14, 1947. Figure 2B shows the same at 16.6 sec in a reduced, but similar, pattern on the Cuttyhunk record of 18^h36^m EST, April 15, 1937. For the separation involved, the travel time appropriate to the group velocity (1.5 times the period) of a 16.9-sec wave is about 22 hr. The record times are thus fairly compatible, especially since swell of such characteristics probably exists for several hours at least. However, according to the wave-decay graphs of the forecast theory, a 16.9-sec wave should progressively increase to 18.8 sec in decaying over 560 mi. This increase is not apparent.

Fig. 3A shows two long-period peaks at 15.4 and 17.1 sec at 22^h36^m, April 19, 1947, Bermuda. Fig. 3B shows two peaks on the Cuttyhunk records at 15.6 and 17.3 sec at 18^h36^m, April 20, 1947. An increase in period of nearly two seconds is required by the forecast theory. Again this is not apparent from the records in which the Cuttyhunk and Bermuda patterns are very similar. In the comparison of records during a one-month interval, six sufficiently distinct cases were noted in which no significant period change occurred. In many of the cases, the presence of numerous peaks on one or both of the spectra compared, prevented application of this method.

The study of the records thus far suggests that this long swell travels through the ocean at a constant or nearly constant period and that such swell travels with the group velocity dependent on the period. BARBER and URSELL [1947], and DEACON [1949] in Great Britain have achieved good results using the assumption that "... waves travel with a group velocity appropriate to their period on arrival."

It is suggested in line with this assumption that a serious discrepancy reported between forecast and observed arrival times for swell from two Pacific storms may be explained. Discrepancies noted by HERMANSON and STUMP [1945] are summarized in Table 2.

Table 2--Forecasts vs observations for two Pacific storms

Item	Storm A	Storm B
Forecast period	16.4 sec	14.8 sec
Observed period	16.0 sec	15.6 sec
Forecast arrival time	Jan. 22, 1945, 21^h00^m	Jan. 24, 1945, 01^h00^m
Observed arrival time	Jan. 21, 1945, 20^h00^m	Jan. 23, 1945, 00^h00^m
Distance traveled	2051 naut mi	1325 naut mi
Forecast travel time	100 hr	68 hr
Group velocity travel time (for observed periods)	85 hr	56.5 hr

The error in the arrival time is 25 hr in both cases. However, if it is assumed that the 16-sec and 15.6-sec waves were generated in these storms, and that they traveled over the decay distances given, the arrival times for Storms A and B become January 22, 1945, 06^h00^m, and January 23, 1945, 13^h30^m, respectively. This reduced the discrepancy to 10.5 and 13 hr for the two storms, respectively. Part or all of this may result from errors in the decay distances, unavoidable owing to the widely scattered wartime marine reports on which the weather maps were based. Also, the wave and swell forecast based on these maps involve many subjective considerations.

Storm swell

The nature of the swell resulting from two Atlantic storms, referred to here as Storms C and D, will be considered in this section.

Storm C, July 6 to July 7, 1946--Commencing about 01^h30^m, July 6, a storm which had been developing slowly for the preceding 12 hours began a slow northeastward motion, following the track shown in Figure 4. After passing out to sea, the forward motion increased to about 20 knots as shown by the six-hourly positions along the track. The wind velocity increased simultaneously until the storm resembled a true tropical cyclone except for the lesser winds which probably never exceeded 45 to 50 knots. Figure 5 shows portions of the wave record made by this storm. The record of conditions six hours earlier is also shown for comparison. The increase in height and period with the arrival of the storm swell on 19^h05^m EST, July 7, is notable.

Although the isobars are not shown, it can be seen from the storm track that the end of the fetch was close to the recording station. The decay distance actually decreased from approximately 240 to 140 nautical miles. Further, the storm crossed the "window of approach" to the station fairly rapidly. As a result, arrival times of waves of different periods become quite critical. Unfortunately, the time interval of six hours between recordings prevents adequate study of this feature.

Application of the forecast theory to this storm results in a maximum expected period of from eight to nine seconds, and maximum heights close to 20 ft. With the short fetch of this storm the forecast graphs require wind velocities near 150 knots, or excessively long duration times for lesser velocities for the production of 14-sec waves, regardless of height.

The decrease in period with time as shown in Table 3 is significant and must be related either to wind changes in the storm or to the position of the storm. Further discussion of this is reserved for consideration under Storm D, where the data are more numerous.

Storm D, tropical cyclone, September 12-15, 1946--Figure 6 presents three successive positions of this storm. As regards size, shape, and wind velocity, this disturbance was a true tropical cyclone. Its forward motion varied from about 15 knots near the beginning to nearly 30 knots in the northern part of its course.

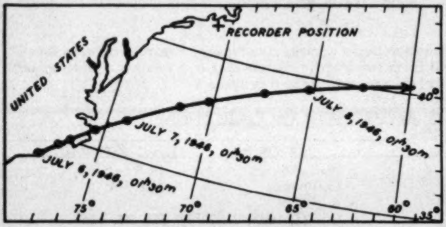

Fig. 4--Track of storm of July 6-7, 1946; storm center is shown for every six hours

In storms of this nature, it has already been shown [U. S. NAVY, CHIEF OF NAVAL OPERATIONS, 1945] that the magnitude of the emitted swell depends on (1) the wind velocity within the storm, and (2) the length of time the waves are affected by the wind, which is largely dependent on the speed of the storm. It is also a generally accepted principle that winds in the half of the storm (right in the Northern Hemisphere) in which the direction of motion coincides with

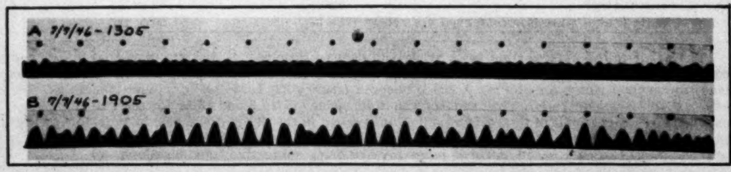

Fig. 5--Comparison of swell recordings at a six-hour interval showing (A) the normal conditions and (B) the storm swell; the dots above each record are 30-second time marks

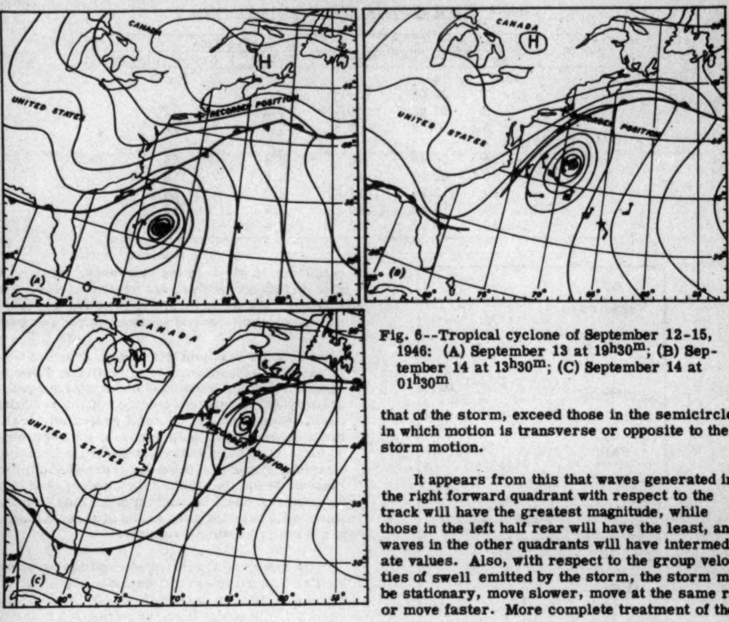
CANADA
UNITED STATES
RECORDER POSITION
H
(A)
(B)
(C)
80°
75°
70°
65°
60°
55°
40°
35°
30°

Fig. 6--Tropical cyclone of September 12-15, 1946: (A) September 13 at $19^{h}30^{m}$; (B) September 14 at $13^{h}30^{m}$; (C) September 14 at $01^{h}30^{m}$

that of the storm, exceed those in the semicircles in which motion is transverse or opposite to the storm motion.

It appears from this that waves generated in the right forward quadrant with respect to the track will have the greatest magnitude, while those in the left half rear will have the least, and waves in the other quadrants will have intermediate values. Also, with respect to the group velocities of swell emitted by the storm, the storm may be stationary, move slower, move at the same rate, or move faster. More complete treatment of these

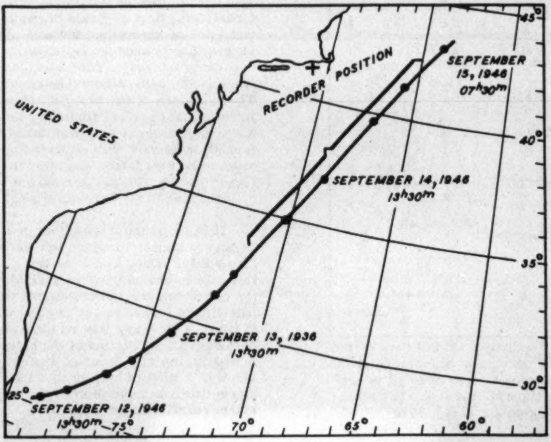
RECORDER POSITION
UNITED STATES
SEPTEMBER 15, 1946 07h30m
SEPTEMBER 14, 1946 13h30m
SEPTEMBER 13, 1936 13h30m
SEPTEMBER 12, 1946 13h30m
25°
75°
70°
65°
60°
45°
40°
35°
30°

Fig. 7--Track of tropical cyclone of Sep. 12-15, 1946

Table 3--Swell characteristics of Atlantic storms

Storm	Recording time		Recorded data		
	Date	Time	Period	Height	Group velocity
	1946	h m	sec	ft	knots
C	July 7	19 05	13-14	7.5	...
	8	01 05	10.5	9.2	...
	8	07 05	9.5	7.3	...
D	Sep. 15	00 50	16	2.4	24
	15	06 50	12	3.6	18
	15	12 50	11	3.6	16.5
	15	18 50	10	1.7	15
	Sep. 16	00 50	9	2.4	13.5

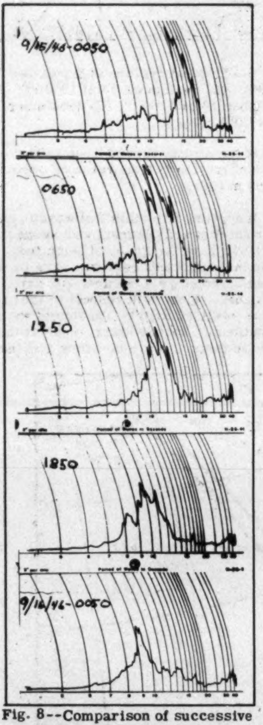

Fig. 8--Comparison of successive swell spectra at six-hour intervals showing decrease of swell period with time for the tropical cyclone of September 12-15, 1946

conditions is given in the reference. Clearly, the time difference between the arrival of swell "fore-runners" and the arrival of the storm depends on the velocity differential between storm and swell.

From the six-hourly storm positions, (see Fig 7), and from an inspection of velocities in Table 3, it i apparent that the movement of the storm equalled or exceeded the group velocities of the resulting swell. Consequently, no swell generated parallel to the storm track could arrive at the recording station. Only when sufficient variation between direction of storm and swell occurred could forerunners be emitted toward the station. And these forerunners would be such in name only, for the storm will have traveled ahead of them, although at a slightly varying direction.

By means of arrival times and the group velocities related to arrival periods, calculations have been made to determine when the recorded swell left the storm track at points that coincided with the position of the storm along the track. Unfortunately, first arrivals of particluar periods could not be used since there is almost a six-hour uncertainty in such arrivals owing to the six-hour recording interval. The bracketed portion of the track is the path of coincidence of storm and swell The extremes of the bracket are not accurate sinc first and last arrival times are not known, and since no allowance has been made for the transformation of wave velocities from deep to shallow water. For the latter condition the velocity no longer varies with the period, but with the depth, h, according to the formula $c = \sqrt{gh}$.

It is found from the above procedure that successively shorter periods left the storm at successively later times along the track. Also, as noted in Table 3, and as shown strikingly in Figure 8, the frequency band representing the storm swell has shifted toward lower periods with the advance of time. (The wavy line on the upper part of each periodogram is a trace of the actual wave record.) In discussion with Maurice Ewing, the generalization was advanced by him that the period of such storm swell is a function of the azimuth of the storm relative to the observer.

A further generalization can be made. If the observed swell decreases in period, the storm is not approaching directly, regardless of small height increases; if the swell increases in height with constant or increasing period, the storm is either approaching directly or turning toward the observer. Although based on actual observations from only two storms, the generalizations advanced seem consistent with present concepts of wave generation within different sectors of tropical disturbances. It is hoped to locate wave instruments at such points that close interval or continuous records will be made of swell emitted from different portions of individual storms. Such accurate observation should help materially in the formulation of simple and acceptable rules of storm swell.

The small height of the swell received from Storm D was probably a result of (1) the greater decay distance compared to that of Storm C, and (2) the effects of refraction and shoals, since the path of approach was for large part beyond the "window of approach" referred to earlier.

Conclusions

From studies of the short-period group the following conclusions are drawn:

(1) The prominent prevailing short-period waves or swell, 5.5 to 10 sec, which approaches Cape Cod (or southern New England generally) are generated by moderate to occasionally strong southerly winds prevailing for one or more days off eastern United States; conversely, the existence of such winds permits qualitative forecasts of expected waves or swell.

(2) The passage of a cold front followed by westerly winds across coastal waters (which were previously affected by southerly winds) does not always close abruptly the interval of generation of these waves. A component of the westerly winds appears to maintain for a somewhat variable period the waves generated by pre-existing southerly winds.

(3) The forecast theory of Sverdrup and Munk appears adaptable to East Coast conditions as regards forecasts of waves at the end of the fetch; height forecasts are quite uncertain.

From studies of long-period swell the following conclusions are drawn:

(1) A long-period swell group, predominantly 14 to 18 sec, appears to approach Cape Cod from the south, passing Bermuda, and has an origin suggested to be the generating area of the Southeast Trade Winds.

(2) Study of this swell, and others referred to in the literature, suggests that ocean swell is propagated with a constant or nearly constant period, and that it travels with a group velocity appropriate to the period.

From storm swell studies the following conclusions are drawn:

(1) The forecast theory of Sverdrup and Munk appears inapplicable to storms in which the velocity of the winds is high and the fetch is short. The maximum wave period in such storms appears to depend mostly on the maximum wind velocity in the storm.

(2) The observed swell period from tropical disturbances or similar storms appears to be a function of the azimuth of the storm. Decreasing periods indicate the storm will pass to one side of the observer. Increasing or constant periods with increasing height indicate the storm is approaching directly or turning toward the observer.

(3) Further study of storm swell by means of appropriately-placed wave meters with frequent or continuous running appears very advisable.

Extension of study--Although this study has endeavored to untangle much of the recognized sea-surface complexities in a particular area, it has at the same time revealed others. Only one such, of particular interest, is referred to here. Occasionally periodogram records have shown swell signatures from 20 to 24 sec. The appearance of these on several successive records six hours apart seems to indicate their validity rather than their being considered as spurious from some instrumental source. Weather maps of the South Atlantic have failed to reveal any possible origin for this group, which must be, with the other problems, reserved for later study.

Acknowledgments

The writer acknowledges gratefully the aid of Maurice Ewing of Columbia University, resulting from his enlightening discussions during the research and manuscript preparation. The investigation has been financed in part under Contract NObs-2083 between the Bureau of Ships, Navy Department, and the Woods Hole Oceanographic Institution.

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SCALE EFFECTS IN HYDRAULIC MODELS INVOLVING WAVE MOTION

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Abstract--A summary of the various instances where wave theories have been verified experimentally is presented briefly. A more detailed discussion is given for those problems where models built to several scales have permitted an evaluation of the effect of scale in the application of data from hydraulic models.

Introduction--Hydraulic models have been used extensively during the last 20 years to investigate various phenomena in connection with the design and operation of engineering works. In only a few instances, however, has the opportunity arisen to permit a comparison between model and prototype results. In most instances where checks on model laws have been possible the investigation pertained to hydraulic structures [AMERICAN SOCIETY OF CIVIL ENGINEERS, 1944]. In the case of problems relating to wave motion the lack of information on the conformity between model and prototype has been due to either the difficulty in obtaining adequate prototype data caused by the usual large size of the prototype or the difficulty of obtaining reliable prototype data because of the inherent variability of waves in nature. In some instances experiments to investigate various wave phenomena have been made with models of various scales. Such tests and the few instances where both model and prototype data are available for comparison constitute the basis of the following brief discussion on checks on some of the model laws of wave motion.

Experimental verification of wave theory--Of fundamental importance in all model studies involving wave motion is the fact that the basic relationships developed from theoretical reasoning have been experimentally verified for both deep and shallow water conditions. Investigations by the BEACH EROSION BOARD [1941] and MITCHIM [1940] have shown that experimental values for wave velocity, mass transport, orbital radii, and wave form agree in most instances within a few per cent with the values given by theoretical equations for these terms. An experimental verification of a theoretical relationship for the energy lost by wall friction in a wave channel has been made by O'BRIEN and CHAFFIN [1942]. A comfirmation of the theory for wave refraction has been made both by the use of models and by field observations. The model studies were made at the University of California by observing wave patterns and wave heights resulting from refractions at a straight beach [WILHOYT, 1940], around a circular island [WILHOYT, 1940], around a breakwater [McCRONE, 1940], and in a submarine canyon [MILNER, 1941]. The observed wave patterns and heights in these studies were compared with the results obtained from refraction diagrams prepared by the graphical method of JOHNSON, O'BRIEN, and ISAACS [1948]. A similar analysis in which observed wave heights were compared with those determined by refraction diagrams has been made for the beach at La Jolla, California [MUNK and TRAYLOR, 1947]. In addition to verification of the theory of refraction, an experimental check has been made on a theory of wave diffraction at breakwaters, this theory being adapted from the theory of physical optics. The experimental checks were made for waves moving around the end of a breakwater [PUTNAM and ARTHUR, 1948] as well as through a breakwater gap [BLUE, 1948]. Investigations have been made in the Fluid Mechanics Laboratory at the University of California to check experimentally the theories for the transformation of waves on a sloping bottom [STELZENMULLER, 1941; PUTNAM, 1945] with the result that the irrotational theory appears to best fit the experimental data. Additional work in this field is still in progress in this laboratory. Theories which have been developed but for which experimental checks have not been made pertain to the loss of wave energy by bottom friction [PUTNAM and JOHNSON, 1949], and the loss of wave energy by flow in a permeable sea bottom [PUTNAM, 1949].

A problem for which a theoretical solution has not been developed and, instead, only experimental work has been made to establish empirical relations, is that concerned with the determination of depths over bottom discontinuities by observation of changes in wave characteristics. Experiments in this field have been made by the BEACH EROSION BOARD [1944] and covered the following conditions: (1) an abrupt discontinuity followed to shoreward by a horizontal shelf at constant depth; (2) an abrupt discontinuity followed to shoreward by a uniformly shoaling bottom; and (3) an abrupt discontinuity, followed by a horizontal shelf, a depression, and a continuation of the horizontal shelf, in order. These tests showed that when waves pass over a reef they may in some instances break up into a multiplicity of waves. A reanalysis of the Beach Erosion Board data for case (1) above by the SCRIPPS INSTITUTION OF OCEANOGRAPHY [1944] showed that even with waves that are broken and deformed, the primary crests undergo a regular change in velocity in crossing the reef, and the ratio, L/L_0, plotted against the ratio d/L_0, lies along a regular curve only slightly above the common theoretical curve for shallow water waves [BEACH EROSION BOARD, 1942]. In this instance L_0 and L represent the wave lengths in deep water and in the region beyond the edge of the reef, respectively, and d is the depth over the reef.

Wind-generated waves--The character of waves produced by a given wind that blows for a known length of time over a known stretch of water (the fetch) has been a subject of considerable interest to mariners and engineers for many years. Prior to 1942 the knowledge on this problem was based entirely on empirical relationships, many of which were of doubtful value. In 1942 SVERDRUP and MUNK [1947] proposed a basic theory of wave generation and, using all available observational data, developed certain relationships between wave and wind characteristics. These relationships, which were presented as dimensionless parameters and hence are model laws, were developed from observations made in the open sea and in relatively small laboratory flumes. It is remarkable that the model law of wind generation of waves would be applicable to conditions where the fetch ranges from several hundred miles, as in the open sea, to only 20 ft in the flume studies of FLINSCH [1946], and only 40 ft in the flume studies of STANTON and Others [1932]. Recent observations on wind waves in lakes tend to confirm the Sverdrup-Munk relationships [JOHNSON, 1948b, 1948c].

Damping of oscillatory waves--The theory of the damping of oscillatory waves by internal friction shows that the travel distance, L_r, required for the wave height to be reduced from H_1 to H_2 is given by the relationship [BEACH EROSION BOARD, 1942],

$$L_r = 1.71\ T^5 \log_e (H_1/H_2)/\nu \qquad (1)$$

where T is the wave period and ν is the kinematic viscosity of the fluid. This equation shows that for waves with periods as small as even one second the rate of damping is tremendously slow. For wave periods considerably less than one second the height reduction due to internal friction becomes significant. Such a condition becomes particularly important in model studies involving refraction or diffraction, or other instances where changes in wave height with travel distance is the factor under investigation. A striking demonstration of the effect of viscous damping was presented in studies that were made to verify the theory for the diffraction of waves at gaps in breakwaters [BLUE, 1948]. In these tests measurements were made of the heights of waves after passing through breakwater gaps of various dimensions. Two sizes of model were used in this investigation. As a typical example, in the larger model with a wave length of 3.8 ft (wave period = 0.86 sec), agreement between theory and experiment for wave heights beyond the breakwater gap was within five per cent. However, for geometrically similar conditions in the small model, where the wave length was 0.71 ft (wave period = 0.37 sec), the experimental wave heights after diffraction were 50 per cent of the theoretical heights. These studies serve to indicate that viscous friction, while negligible for waves longer than a few feet, becomes increasingly important for shorter waves. Studies involving quantitative consideration of heights of waves with lengths shorter than one foot should not be undertaken without some consideration of friction losses by internal friction.

Wave action in the surf zone--To provide information on the character of waves in the surf zone, observations were made by the SCRIPPS INSTITUTION OF OCEANOGRAPHY [1944a]. This investigation consisted of photographing waves as they moved past graduated boards mounted on the piling of the Scripps Pier at La Jolla, California. From these photographs the following information could be determined: wave velocity, wave period, the height of the waves up to the point of breaking, the position of the breaker, and the water depth at the point of breaking. Data from these observations, combined with data obtained in the wave tanks of the Beach Erosion Board and the University of California, were utilized to determine the characteristics of waves at breaking. One important relationship from these studies was the establishment of a "breaker index" curve [U. S. HYDROGRAPHIC OFFICE, 1944] This curve (see Fig. 2) shows the relationship between the wave steepness in deep water (H_0/L_0) and the ratio of the depth of breaking to the deep-water wave length (d_b/L_0); thus, for waves with a given steepness (H_0/L_0) and deep-water wave length, L_0, obtained by a forecast from synoptic weather charts [U. S. HYDROGRAPHIC OFFICE, 1943] the depth at which the waves will break can be calculated. Such information is of value in predicting surf conditions that may occur on a particular beach from waves generated by a given storm.

In contrast to the beaches in the wave-tank studies, where the bottom profile was a straight line, the beach at La Jolla had a single offshore bar as shown in Figure 2. In order to ascertain the nature and characteristics of breakers produced on a beach with such a profile, studies were made in the University of California wave channel on an undistorted 1:40 scale model of the Scripps Beach which existed at the time the prototype wave observations were made in October 1944 [JOHNSON, 1947].

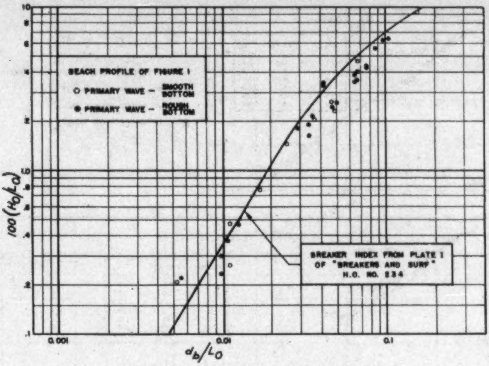

Fig. 1--Relationship between wave steepness in deep water and the depth of breaking for model of Scripps Beach

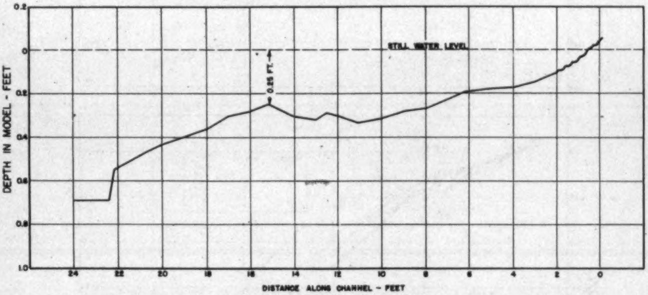

Fig. 2--Profile of beach along Scripps Pier as of October 23, 1944

The beach was molded with sand and then covered with a thin layer of plaster to give a smooth surface. In some tests a rough bottom was obtained by covering the plaster surface with a strip of slate asphalt roofing paper. A wave machine was provided at one end of the channel, and during a test the wave height, wave period, breaker height, and depth of breaking were measured. From these observations the terms H_0/L_0 and d_b/L_0 were calculated. The experimental data are shown in Figure 1 for both a smooth and rough surface. Examination of this figure indicates that the agreement between model and prototype results was good, and that the effect of bottom friction was too small to contribute a measurable influence on the position and character of the breaker.

It is of interest to note that with certain wave steepnesses and depths over the offshore bar the waves broke into primary and secondary waves, such that two lines of breakers appeared on the shore. The conditions under which this phenomena occurs confirmed the experiments made by the BEACH EROSION BOARD [1944] and discussed above to determine a criterion for the transition point where waves break into a multiplicity of waves in going over a reef. Both sets of experiments show that when the value of the experssion $\sqrt{H_0 L_0/d_r}$ is less than 2.0 the transmission of waves over a reef was regular; whereas, when the value of the expression was greater than 2.0 a wave would break on the reef, reform, and then move forward with more than one crest. In the above expression H_0

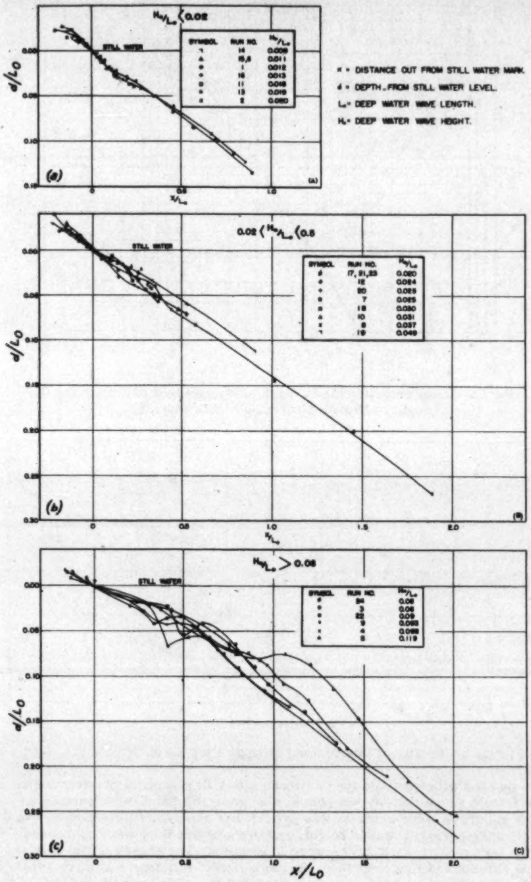

Fig. 3--Equilibrium slopes of sea beaches (data of R. D. Meyer)

and L_0 are the deep-water wave height and length, respectively, and d_r is the depth of water over the reef.

Longshore currents--An important factor in beach erosion studies and in amphibious operations through the surf zone is the longshore current which develops when waves break at an angle with the shoreline. A relationship has been derived from theoretical consideration between the velocity of the longshore current and the height and period of the breaking waves, the angle between the breakers and the beach contours (assumed straight and parallel), and the beach slope in the breaker zone.

Field observations and laboratory experiments support this relationship [PUTNAM, MUNK, and TRAYLOR, 1948].

Equilibrium profiles of sea beaches--A beach is considered to be in equilibrium when the continued application of wave action for an appreciable time is found to produce relatively insignificant changes in the profile of the beach under investigation. Under natural conditions it is doubtful whether an absolutely stable profile is ever attained due to the constantly changing forces of currents, tides, winds, and waves. To study the effect of waves on beaches laboratory investigations have been made at the University of California, U. S. Waterways Experiment Station, and the Beach Erosion Board. In all of the studies the effects of currents, tides, or winds were eliminated and only the condition with waves moving directly onto a beach was considered.

In the investigations at the University of California [MEYER, 1936; WATERS, 1939] the procedure was to place a particular material in the wave basin, adjust the wave generator to constant conditions of wave height and period, and then allow wave action on the beach to continue until an equilibrium condition of the beach profile was attained. The results indicated that the profiles may be classified either as "ordinary" or "storm." An ordinary beach has no distinct offshore bar formed by wave action, while a storm beach generally has an offshore bar in the region of the plunge point and may have, in addition, one or more intermediate bars.

The deep water height-length ratio (H_0/L_0) of the waves alone seems to determine which of the two types of profiles a beach will assume. This relationship is best illustrated by Figure 3 where dimensionless plots of the profiles obtained from tests on one particular sand are shown. To avoid confusion, the profiles for various conditions of wave conditions have been plotted in separate diagrams. Figure 3A shows the equilibrium profiles for runs in which the values of H_0/L_0 was less than 0.02; Figure 3B applies to runs where H_0/L_0 was between 0.020 and 0.05, and Figure 3C for H_0/L_0 values greater than 0.05. For the material used in these particular tests it was found that the ordinary type beach always formed in the wave tank when the value of H_0/L_0 was less than about 0.025; while for H_0/L_0 values greater than 0.03 storm beaches always formed. For H_0/L_0 values between 0.025 and 0.03 there appeared to be a transition zone where either type of beach might exist. A total of six sands was tested in this study.

Some tests were made in which the beach first was subjected to waves with H_0/L_0 greater than 0.03, in which cases the storm profile always developed. The value of H_0/L_0 then was reduced to less than 0.025, in which case the offshore bars of the storm profile always disappeared, and the beach assumed an ordinary profile.

It is of interest to mention that for each profile in the above experiments the slope at the still-water line was determined and plotted against the ratio H_0/L_0. Also, for the storm beaches the offshore slopes of the bars were determined and plotted against H_0/L_0. In all of such plots little or no relationship between H_0/L_0 and a single slope term appeared adequate to properly define an equilibrium profile. Instead, a dimensionless plot of the profiles as illustrated by Figure 3 appeared the most reasonable method of summarizing results.

Other experimental work on wave action on beaches that is of interest to summarize in connection with this discussion is the work done at the U. S. WATERWAYS EXPERIMENT STATION [1940]. Investigations were made to obtain comparative results from three model beaches in which all elements were reproduced with the scale relations of 1:2:3; that is, the smallest wave tested was studied again at twice its original size and then again at three times its original size. The beach was molded to a 1:5 slope from the bottom of the wave tank to well above the upper limits of wave action. The bed was subjected to wave action until stability was obtained. The similarity of profiles obtained from comparable setups and the close agreement between the stable slopes resulting from these tests, with a given material, were both indicative of the fact that a small-scale study of wave action on various materials could be used in studying full-scale wave action on identical materials.

The BEACH EROSION BOARD [1947] tests were similar to those conducted at the University of California [MEYER, 1936; WATERS, 1939] and at the U. S. WATERWAYS EXPERIMENT STATION [1940]. To define the influence of the several factors which determine the equilibrium profiles of beaches, tests were made by molding one sand to various slopes and subjecting these slopes to three different wave conditions. Preliminary results from these tests indicate that, within the limits of the test conditions, the height-length ratio of the waves and not the original beach slope is the important factor in determining the character of the equilibrium profile.

Some studies have been made to test the reliability of relatively small scale models for giving information on sand movement and beach erosion [JOHNSON, 1948a]. The method used was to construct models of portions of a shoreline and compare the model results as obtained by varied conditions of littoral drift and wave action with known results in nature. The results from these studies are primarily of a qualitative value and considerable more study is required to adequately define the relationships between sand movement along a beach and wave conditions. Some thoughts on the organization of a research program on the movement of beach sand by water waves has been expressed by EINSTEIN [1948].

Breakwater stability--In model tests made at the U. S. WATERWAYS EXPERIMENT STATION [1948] to determine the most efficient design of a composite rubble-mound breakwater an occasion presented itself to verify the equations used for the transfer of data between model and prototype. This investigation consisted of tests on three models constructed to scales of 1:30, 1:45, and 1:60 of a typical prototype design. The sizes of the model stones were chosen so as to obtain rock particles the weights of which would bear a definite ratio to the prototype specifications. Each model was placed in a wave tank and subjected to wave action until a stable profile was reached. A comparison of the stability profiles between the three models showed good agreement, and it was concluded that the Froude model law applied in such a problem. It was demonstrated that model breakwaters should be founded upon materials which have friction coefficients and interlocking characteristics similar to those of their prototypes.

Surging in harbors--History records many instances of the damage and destruction of dock facilities, breakwaters, jetties, and other engineering structures by surging in a harbor, bay, or other semi-enclosed body of water. Some of the forces which initiate surfing are the drag effect of wind blowing over the water surface, variation of atmospheric pressure, the ocean tide and swell acting on a bay or estuary, and underwater earthquakes. To obtain basic data on the phenomena of surging, an experimental investigation [BROSHOUS, 1938] was made in a channel 25 ft long, six inches wide, and 18 inches deep, in which a power-driven plunger was provided near one end to give a forced oscillation. A float type recorder was located on the ooposite end of the channel from the plunger and was used to measure the height and period of the oscillations. Experiments were made both with a horizontal bottom in the channel (constant depth) and a parabolic bottom (variable depth). The damping effect of sills of various heights and location also was investigated.

The experimental results were plotted to show the relation between amplitude of oscillation and the period of the plunger for two rectangular basins and one basin with a parabolic bottom. From the plots for the rectangular basin it was found that at particular periods of the plunger the amplitude of oscillation of the water became many times greater than the amplitude for any of the periods between these points. Those periods where the amplitude was greatest were the points of resonance for the particular channel involved, and should, if the theory of surging is correct, be verified by the constant depth formula; that is,

$$T = 2L/(k\sqrt{gD}) \qquad (2)$$

where T is the period, L and D are the length and depth, respectively, of the basin, and k is a whole number. A comparison between theory and experiment for various types of surging is given in Table 1 for two rectangular basins.

Table 1--Comparison between experimental and theoretical periods of seiches in rectangular basins

Type of seiche	Basin 1 (L = 25.17 ft, D = 0.735 ft, W = 0.5 ft)		Basin 2 (L = 22 ft, D = 0.9 ft, W = 0.5 ft)	
	Measured	Computed	Measured	Computed
	sec	sec	sec	sec
Uninodal	10.35	10.34	8.05	8.18
Binodal	5.12	5.17	4.04	4.08
Trinodal	3.46	3.45	2.75	2.73
Quadrinodal	2.64	2.59	2.11	2.05

The close agreement of the measured and computed periods shown in Table 1 clearly indicates the validity of the theory for constant-depth seiching. One of the factors which might account for the slight slight discrepancy effect of the plunger and recorder float in modifying the effective lengths and depths of the basins.

Comparison of computed data with experimental results also was made on the basin of variable depth. The basin in this case was 24 ft long and six inches wide with the bed molded to the shape of a truncated parabola. The maximum depth of one foot was at the center and the depth was 0.7 ft at the two ends. Theoretical periods were computed by several different methods which are described below briefly.

The theoretical equation for the period of a seiche in any channel is

$$T = 4\int_0^{L/2} dx/(K\sqrt{gD_x}) \qquad (3)$$

where D_x is the depth at any distance x from the end of the basin. The other terms in this equation were defined in connection with (2). If, however, the wave height H is not small in comparison to the depth, the wave velocity, C, is given by equation

$$C = \sqrt{gD}\,(1 + 3H/2D + \cdot\cdot)$$

hence, if higher order terms in the progression are neglected, (3) should be written as

$$T = 4\int_0^{L/2} dx/[k\sqrt{gD_x}(1 + 3H/2D_x)] \qquad (4)$$

A comparison between theoretical and experimental periods for various types of seiches is given in Table 2. The theoretical values in the third column of this table were obtained by the use of (3), where the entire 24 ft of the basin was considered to be the length L. The values of period in the fourth column were computed by the same formula, except that L was taken as the distance from the face of the plunger to the opposite end of the basin (that is, L = 22.53 ft). The values in the fifth column were computed from (4) where the height H was assumed to be one-half the measured amplitude of the oscillation. In the last column the values of period were computed from the equations for a truncated parabola as developed by CHRYSTAL [1906].

Table 2--Comparison between experimental and theoretical periods of seiches in a basin with a parabolic bottom

Type of seiche	Observed	Theoretical			
		Eq. (3) L = 24 ft	Eq. (3) L = 22.53 ft	Eq. (4)	Chrystal
	sec	sec	sec	sec	sec
Uninodal	8.91	10.04	9.19	9.28	9.02
Binodal	4.80	5.02	4.59	4.67	5.03
Trinodal	3.31	3.35	3.06	3.16	3.53
Quadrinodal	2.58	2.51	2.30	2.62	2.76

A comparison of the various computed periods in Table 2 with the observed value indicates that the plunger probably reduces the effective length of the channel and also that the effect of finite height of the seiche should be considered. The results from using Chrystal's equations show a maximum deviation from experiment of 7.5 per cent for the quadrinodal seiche and a minimum deviation of 1.2 per cent for the binodal seiche.

The investigations on the damping effect of sills were made in a rectangular basin 22 ft long, six inches wide, with a water depth of nine inches. Sill heights of 0.225 and 0.45 ft above the bottom were placed at various positions in the basin and the amplitude of oscillation measured for various plunger periods. The maximum reduction in the height of oscillation was obtained when a sill was placed at the nodal point. Thus, for all periods, with the 0.45 ft sill a maximum reduction in height of oscillation of 80 per cent was observed, and with the 0.225 ft sill this maximum reduction amounted to 55 per cent of the height obtained without the sill in place. For both sill heights it was found that the sills could be moved away from the node a distance up to 50 per cent of the total distance from the node to the end of the basin without decreasing the magnitude of the maximum reduction in height of oscillation by more than about ten per cent. This latter observation that a sill need not be located exactly at a node for maximum efficiency is of practical importance in the design of sills for reducing seiching in a harbor or other navigable channel; that is, considerable leeway exists as to the choice of location of a sill without appreciably affecting its efficiency in reducing the heights of surges.

Summary--The above discussion summarizes briefly the instances where various theories pertaining to problems involving oscillatory waves have been verified experimentally. Also discussed are those instances, known to the writer, where models of several sizes have permitted a check on model laws. The various investigations that are summarized above indicate some of the phenomena that are encountered in engineering and oceanographic investigations and which are susceptible to solution by the aid of hydraulic models.

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DEVELOPMENT OF A NEW THERMAL FEATURE IN YELLOWSTONE NATIONAL PARK

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Abstract--Norris Geyser Basin in Yellowstone National Park is characterized by great variations in location and activity of thermal features. A new and popular "geyser" developed in the center of a paved parking area, in the spring of 1946. Observations on the types and changes of activity of this feature are recorded for a three month period. Late phases of activity appear to be directly related to the frequency of local rainfall and the resultant effect upon ground water circulation.

Observations--On May 22, 1946, at 09^h33^m, a new and violent thermal feature broke through the macadam pavement of a parking area 150 feet east of the Norris Museum, Yellowstone National Park. This feature received wide publicity, throughout the United States, as a new geyser.

The initial outbreak of steam was observed by visitors, who had parked their cars in the area. Steam and fluid mud worked up through cracks formed in the pavement. As the action continued, mud flowed over the macadam surface to a depth of several inches. As mud and base course material were removed from below, the pavement surface progressively foundered, forming a small caldron two by three feet filled with viscous mud. Motion pictures taken of this new "geyser," in its formative stages, show violent "boiling" and mildly explosive types of action accompanied by undermining and collapse of the pavement. The term "boiling," as used herein, is intended as descriptive of a type of action rather than implying attainment of a boiling point. Continuous explosive activity occasionally threw droplets of mud as high as fifteen feet. In this manner, a flat shield type cone, about 10 inches high, was formed around the rim of the caldron. Undermining of the pavement continued for 48 hours to form a crater measuring 12 x 15 feet from rim to rim. After reaching this size, "boiling" activity subsided, with water standing about one foot below the pavement level.

The water level remained at this level with "boiling" action about eight inches in height until June 24. On that morning, at 08^h00^m, the water level rose to within one inch of overflowing the lower (west) rim. The feature was observed closely during the day in anticipation of seeing a pronounced overflow. By the end of the day no overflow had occurred, so an early morning (06^h00^m) check was made on June 25. Water was still standing high in the caldron. At 08^h00^m that morning, the caldron was completely dry, exposing a 45 degree conical crater, six feet deep, lined with gray kaolinitic clay. The orifice at the bottom was about ten inches in diameter, but clogged with coarse gravel. By 09^h00^m of the same day, water had returned to the crater and had risen to a depth of two feet. The return of water was accompanied by violent "boiling" about three feet in height. At 09^h05^m, the "boiling" subsided, only to be followed at 09^h10^m by violent "boiling" activity.

While "boiling" activity continued, the water level began to fall rapidly, leaving the crater dry at 09^h20^m. Escape of steam and the deep rumbling of "boiling" could be heard from the orifice until 10^h30^m, when water reappeared. Two feet of water stood in the caldron with violent "boiling" (throwing mud and water three to four feet high) until 10^h40^m, when the action ceased. Water quietly disappeared at 10^h50^m. At 11^h50^m two inches of water quietly rose through the gravel clogged vent and remained at that level until 13^h00^m, when it rose with some violence to a three foot depth. Vigorous "boiling" action continued until 19^h00^m, when once more the surface became placid. On the morning of June 26, the crater was half-full and "boiling" mildly. At this time the crater measured 18 feet north-south and 15 feet east-west. (The dimensions of the crater have not changed, up to the date of writing of this paper, April 1949.)

From June 26 until July 14, the water level subsided at a uniform rate of one inch per day. "Boiling" activity, about eight inches in height, continued throughout this period. During the above 19-day interval of comparative quiescence, it was possible to record fluid temperatures below the surface of the actively "boiling" and continuously thickening mud in the caldron. Table 1 records the maximum temperatures observed 12 inches below the surface in the center of activity and at the borders of the pool.

The boiling point of pure water computed for the elevation of the new thermal feature is 92.25°C. Thermal waters can not be considered as pure, for the determination of the boiling point. It is notable, therefore, that the recorded temperatures of the pool, range from 3.75°C to 8.25°C below the normal boiling point for the locality. Facilities were not available for the analysis of effluent water and gas and content of solids. Therefore, a boiling point determination has not been made for the pool. Such a figure would be of interest in recognizing the physical reaction responsible for the violent eruptive phases. At the time of greatest activity, the writer interpreted the action as being caused by the escape of gases at temperatures below the boiling point of the heavily laden solutions. In the absence of accurate composition determinations, it appears probable that the higher observed temperatures may actually have attained the boiling point, and that true boiling was responsible for the activity. Under the latter condition, a considerably smaller volume of gas was evolved than originally recorded.

Table 1--Representative temperatures

Date	Time MST	Temperature	
		Center	Borders
1946	h m	°C	°C
July 12	11 00	88.5	71.1
July 13	11 00	87.6	70.5
	19 00	84.0	67.0
July 14	14 00	87.5	70.5

On July 15, 1946, the last of the water in the caldron drained out through the orifice, against a noticeable volume of escaping gas and steam. (Arsenic and hydrogen sulphide gases were readily detected.) The crater remained dry for the next eight days with audible escape of unusually "dry" gas from the vent. On July 23, the crater was dry at $08^{h}00^{m}$. After a cloud-burst and hail storm at $10^{h}00^{m}$ the crater had filled to a depth of two feet. Vigorous "boiling" action continued for the following three days, while the water level fell gradually. During the evening of July 26, a sudden rise in the intensity of the sound of escaping steam attracted the writer's attention. The remaining water in the caldron had apparently drained out quickly, once more permitting the free and noisy escape of steam and gas from the clogged orifice.

The crater remained as a gaping dry hole in the pavement, for the following four days. Another heavy rainstorm, on July 30, caused the rise of eighteen inches of water. Vigorous "boiling" continued until all water disappeared on August 1.

For the remainder of the summer observation period, this feature continued as a fumerole. After the above date, meteorological conditions showed no effect on the type of activity. Rain gages and other meteorological equipment were not available for direct correlation of thermal activity with atmospheric conditions. Previous to the partial filling of the crater, by the rainstorm of July 23, no meteorological control of activity could be inferred. (Only occasional weather observations and thermal activity were simultaneously recorded.) Because of the crowning of the parking area surface and the low shield type cone, produced during the early stages of activity, no surface drainage could enter the crater. Variations in the volume of water within the crater must be ascribed to fluctuations in the volume and availability of circulating ground water.

Recent personal correspondence with the Yellowstone National Park, Park Naturalist, David Condon, indicates that this new thermal feature has continued as a fumerole since September, 1946.

It is well to note that this feature has never been a true geyser. More accurately, the new feature at Norris Museum was a mud pool in infancy, which has now reverted to a fumerole.

Acknowledgments--The first month's observations, complete with motion pictures, were made by David Condon, Park Naturalist. Parts of this paper were published by the writer [TURNER, 1946] while on the Naturalist Staff in Yellowstone Park.

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APPLICATION OF FLOOD-STORAGE ACCOUNTING METHODS

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Abstract--This paper discusses day-to-day application of the author's method of flood-storage accounting as used in flood-forecasting studies on the Roanoke River above Buggs Island Dam Site in Virginia. Use is made of data from six telemark installations at river gages above the Dam Site. This method has been used to predict successfully the flood rises on the Roanoke River.

Runoff on a large watershed may be determined from stream flow during storm rainfall of flood-producing magnitude by application of storage-accounting methods. An earlier paper [CLARK, 1944] showed that this might be accomplished fairly accurately with a reasonable number of stream gages. This paper shows that usable results may be obtained using a small number of well-located river gages.

The determination of runoff from rainfall is not practicable for some organizations with small staffs and moderate budgets. In the mountainous areas of the eastern United States, the attempts to do so are discouraging, even when funds are available for maintenance of a large number of radio reporting rain gages, and for the personnel to analyze the voluminous data. Only a large number of gages can reveal the erratic rainfall distribution of such an area. A wide variation in infiltration capacity of soils also exists. A theoretically sound application of infiltration theory, of a rainfall-runoff relationship, is discouragingly unsatisfactory. In practice, a determination of volumes of runoff is used to compute rates of stream flow, and then the runoff estimate is revised to provide more satisfactory reproduction of the stream flow known to be taking place. After the first such revision, the runoff volumes are no longer determinations from rainfall, they are determinations from stream flow.

The runoff determination from stream flow, however, is also influenced by the flow calculating routines; defects of the routines become defects of the determination. Few unit hydrographs, or flood-routing techniques, are completely satisfactory in all details. Fewer storms are either uniform or like the ones from which unit hydrographs were developed. Consequently, after an estimated runoff value is used with these tools to compute an expected flood hydrograph, and when that estimated runoff has been revised to support computations which more closely approximate the known portion of the unfolding flow records, the revised value becomes something else than a true value of runoff. The runoff by this time is not runoff at all; it is only a determination of the arithmetic value of apparent runoff which, when used as runoff with the applicable flow calculating methods, indicates the rates of flow and volumes of valley storage which are consistent with the record being observed. The determination of runoff has thus become an inverse application of unit hydrographs and flood-routing principles and techniques. One systematic inverse procedure for determining flood volume available for runoff has been presented [CLARK, 1944].

Where a sufficient number of stream-flow data are used in the flood-storage accounting procedure, and flow-calculation routines are well determined, a quite satisfactory determination of runoff can be made. Such a determination may be as accurate as any other determination as was demonstrated in the original article on this subject.

However it would appear that the method might be useful even if based upon considerably fewer stream-flow data. A qualitative loss of accuracy would be expected; gages widely spaced along a river could hardly indicate the volumetric contents of the river channel as completely as closely spaced gages. Nevertheless, there are many watersheds under 10,000 sq mi in which a creditable job of forecasting is being done with daily observations of a half dozen stream gages and as many precipitation gages. Perhaps a rather large degree of inaccuracy and inadequacy of data could be tolerated before the storage-accounting method become any less accurate than required for such purposes.

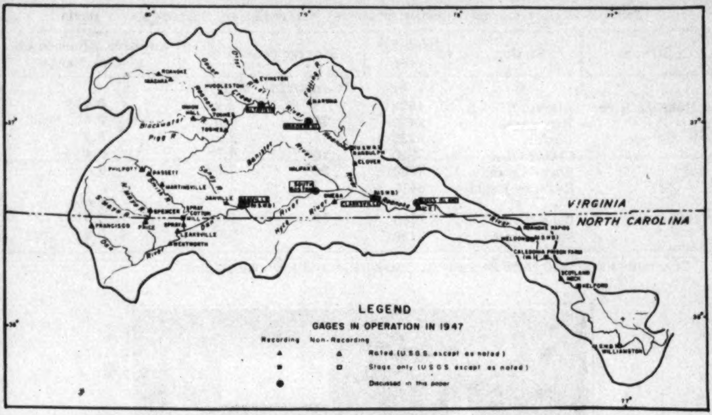
80°
79°
78°
77°
37°
36°
ROANOKE
MAGNA
EVINGTON
HUDDLESTON
Goose
Otter
Creek
River
Falling R.
BRIDGEWATER
TOBIES
Blackwater
Pigg R
Banister
River
HALIFAX
CLOVER
PHILPOTT
BASSETT
MARTINSVILLE
Smith R.
N. Mayo R.
S. Mayo R.
SPENCER
SPRAY COTTON MILL
FRANCISCO
PRICE
LEAKSVILLE
WENTWORTH
Dan
River
Sandy
DANVILLE
SOUTH BOSTON
Hyco
CLARKSVILLE
Roanoke
River
VIRGINIA
NORTH CAROLINA
ROANOKE RAPIDS
WELDON
CALEDONIA PRISON FARM
SCOTLAND NECK
PALMYRA
WILLIAMSTON
LEGEND
GAGES IN OPERATION IN 1947
Recording
Non-Recording
▲ △ Rated (U.S.G.S. except as noted)
■ □ Stage only (U.S.G.S. except as noted)
● Discussed in this paper

Fig. 1--Stream-gaging stations, Roanoke River Basin

The Roanoke River is in southern Virginia and the adjoining part of North Carolina. It flows eastward from the Blue Ridge Mountains to the Atlantic Ocean. The Watershed, its principal streams, and the gaging points discussed herein are shown in Figure 1.

Records from recording stream gages that have been in operation for a decade or more were used to work out the basically applicable storage-accounting methods. A small group of six of these stations which appeared to be most useful were chosen to determine the feasibility of using so small a number. This group of stations with minor modifications of location dictated by practical considerations are listed in Table 1. Each station was equipped to report by telephone and day-to-day operations were undertaken, to forecast floods for construction purposes at a dam on the Roanoke River at Buggs Island.

Table 1--Valley storage in major watercourses of the Roanoke River[a]

Stream	Gaging station	Drainage area	Valley storage[b]	
		sq mi	Per cfs ac-ft	Per cfs in one sq mi
Roanoke River	Altavista	1802	0.40	720
	Brookneal	2420	2.25	5,450
	Clarksville	7320	1.83	13,400
	Buggs Island	7800	0.50	3,900
Dan River	Danville	2054	1.32	2,710
	South Boston	2730	1.54	4,200
Total above Buggs Island		7800	3.89	30,380

[a] For storage accounting above Buggs Island in terms of records at listed gages only.
[b] In major watercourses only; storage in minor watercourses is approximately 3.5 ac ft per cfs of inflow to major watercourses.

The forecasts have been in progress for about two months (February 1948). Mechanical problems are still to be improved upon. Runoff volumes have been indicated quite usefully, and flood forecasts made have been impressive. A recent flood from melting snow and light rainfall would have been unpredictable by the rainfall-infiltration-runoff techniques in use in the area. But a flow prediction, based on flood storage accounting and made during the period of snow-melt more than 12 hr before any streams were known to have crested, proved to be less than ten per cent too high. The volume of runoff may have been underestimated slightly. There is no decisive way to prove quality in this period in which normally applicable methods would have been confounded by freezing, thawing, protracted snow-melt, well-saturated ground, and intermittent light rain.

Table 2--Valley storage capacity of natural watercourses, Roanoke River Basin

Stream	Station	Drainage area	Storage constants		Relative influence of upstream gage
		sq mi	cfs-hrs/cfs	ac ft/cfs	
Roanoke River	Altavista	1802	12	1.0	0.4
	Brookneal	2420	36	3.0	0.4
	Clover	3230	14	1.2	0.2
	Clarksville	7320	10[a]	0.8[a]	0.4
	Buggs Island	7800	24[a]	2.0[a]	0.4
	Roanoke Rapids	8410	. .	. . .	. .
Dan River	Danville	2050	32	2.7	0.5
	South Boston	2730	9	0.8	0.3

[a] Constants estimated from records at Clarksville and Roanoke Rapids.

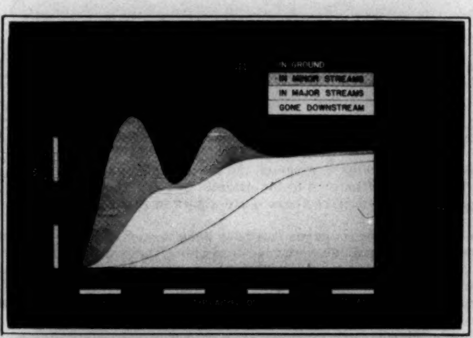

Fig. 2--Application of storage-accounting method to a theoretical flood

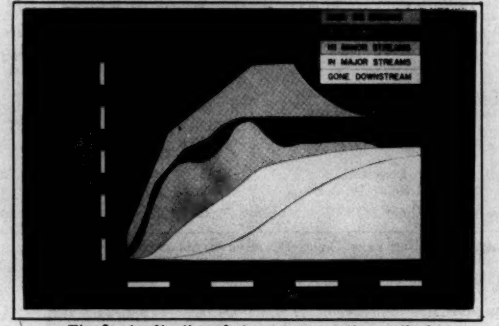

Fig. 3--Application of storage-accounting method
to floods whose record was known

The development of the six-station accounting technique follows the sequence of the earlier paper [CLARK, 1944] and needs no special explanation. Tables 1 and 2 give the applicable constants. The application of the storage-accounting methods are illustrated by Figures 2 and 4.

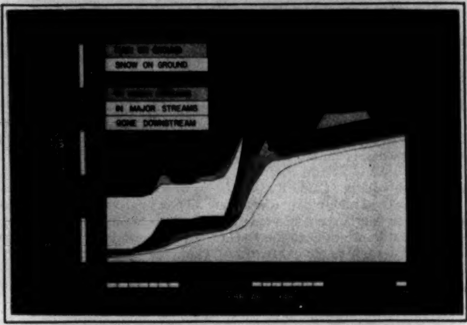

Fig. 4--Application of storage-accounting method during one of the first two months of day-to-day operations

Figure 2 shows application to a theoretical flood. It is in such a flood that the constants are determined and checked. Figure 3 shows an application to a flood whose record was known. Passing forward from studies of past records to current records, Figure 4 shows an application of storage accounting during one of the first two months of day-to-day operations. It was based upon telephone calls to automatic reporting gaging stations made as deemed necessary; it was also subject to a few human and mechanical shortcomings, some remediable, which kept these examples from being completely judgment free.

A few of the defects of storage accounting become more obvious when applied to records of only a few stations. Thus, for example, storage may get lost between two gages a great distance apart. That is, the presence of storage in the reach may be indicated by an upper gage near its crest, and the total indicated volume of storage in major watercourses may actually decrease before the downstream gage registers the passing peak and a corresponding large volume again. Interpreted by the automatic mathematics as inflow to major watercourses, and therefore indicative of storage in minor watercourses, this alternate decrease and increase in major watercourse storage causes a marked fluctuation of the mass curve of inflow to minor watercourses (see Fig. 2 near end of second day). In a rain-free period, this fluctuation would be recognized for what it is, inherent error, but what would be its interpretation if the rise occurred during noticeable rainfall?

A satisfactory technique is still to be found for accounting for storage in subsurface watercourses. Examining Figure 2, the reader will note the attempt to approximate the runoff which produced the flood with three basic volumes, that is (1) volume gone downstream; (2) storage in major streams; and (3) storage in minor streams. One important volume, storage in the ground or in sub-surface watercourses lies between the mass curve of inflow to minor streams and the mass curve of runoff which produced the flood. Two basic techniques were used for determining this storage in the ground. Neither is thought to be adequate for routine application by judgment-free methods; each has limited usefulness.

Subsurface storage can be estimated in the same manner that surface storage in minor watercourses has been estimated, by assuming that the flow from that storage is directly proportional to the storage. If this were true, subsurface storage could have a value expressed in either of the following ways

$$S_S = K_S Q_S \quad \text{.............................} \quad (1)$$

or

$$S_S = Q_S^2/(dQ_S/dt) \quad \text{.........................} \quad (2)$$

where S_S is storage in subsurface watercourses; Q_S is flow from storage in subsurface watercourses; and K_S is a constant of proportionality.

Such simple relationships should be less difficult to apply. The problem is, of course, to determine the value of flow from subsurface watercourses to which the constant, K_S, is to be applied. The writer applies the values in periods of protracted low flow; mostly as a check on judgment applied during flood flows. Usefulness is largely due to the fact that when applied to flow which also contains some non-subsurface flow, one equation gives too large a value, the other too small, and the two values may converge on a suitable value. Fundamentally, the usefulness is artificial. Considering that the distinction between subsurface flow included in unit hydrographs and the base flow or ground-water flow excluded therefrom is wholly arbitrary, the principal question is one of consistency. How much subsurface volume goes with the unit-hydrograph or the flood-hydrograph computing technique in use?

In the technique of the author [CLARK, 1945], in which consistency is valued above accuracy, and as applied to the watershed under consideration, 30 per cent of the unit hydrograph is composed of subsurface volume originating in a subsurface-storage reserve of 200 cfs-hrs per cfs. (Values are not general, but applicable to the watershed discussed herein.) These proportions are built into the unit hydrograph in its derivation. Thus, for these unit hydrographs of Roanoke River, the constant K_S is 200 cfs-hrs per cfs, or 16.7 ac ft per cfs. The two equations were applied in estimating volume in the ground as shown on February 10 and February 19 in Figure 4.

The second approach to subsurface storage, also faulty, is an extension of the storage-accounting technique developed in Figure 2. In that diagram it will be noted that inflow to minor streams (the total volume in minor and major streams, or gone downstream) fails to agree with runoff which produced the flood (the same amounts plus the volume in ground) by notable amounts reaching a maximum in the third day. It is expected, then, that the storage-accounting procedure will result in a similar deviation whenever applied. The deviation which may be either subsurface storage or error, is therefore expressed as a percentage, reduced to unit hydrograph form, and applied to the runoff thought to be on the watershed at any time to determine the runoff likely to be unaccounted for at some later time. The writer computes the value occasionally, to guide his judgment in plotting a mass curve of runoff like that shown on Figure 4 but does not rely upon it.

A forecaster concerned with the high utilization of flow, as in operation of a reservoir for power and flood control would be concerned with some other volumes. Some of these data would come from other sources than stream flow. There would be a forecast of rainfall; that is potential runoff but by no means assured runoff. Rainfall and snowfall are potential runoff, and their occurrence constitutes a revision of the forecast precipitation. As long as it is not certain that precipitation has vacated the watershed by some other means than as runoff, it must be assumed to be on the watershed, and still potential runoff. Nevertheless, when it does leave as infiltration, evaporation, transpiration, or as just wrong data as to the original amount, the disappearance is negative flow into the watershed and shows in a mass-curve as a decreasing ordinate. From day-to-day, the forecaster modifies his estimates regarding the quantities indicated by his data; the mass curve of potential runoff goes up or down accordingly. The day-to-day representation of these elements, as the writer finds it convenient to represent them, are shown in Figure 4. It is upon a drawing like Figure 4, that flood forecasts and floodtime reservoir operations are predicted.

Storage accounting, at this writing, is deemed to produce a useful index to prospective flow in the form of the indicated accumulation of inflow to minor watercourses. Under some circumstances this index closely approximates inflow to the watershed, or runoff. Calculation can be accomplished without the exercise of judgment by the computer. With some additional judgment, runoff is easily approached.

Comparison of the runoff volumes indicated by storage accounting with the rainfall indicated shows a sufficiently high correlation to justify the anticipation of reasonable accuracy in the runoff determination. Low cost will encourage usage in spite of remaining limitations.

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A MANOMETRIC SETTLING-VELOCITY TUBE

Martin A. Mason

Abstract--A theory is developed for a manometric settling velocity tube which permits rapid, accurate determination of still-water settling velocities of sediments in the sand-size range. A preliminary design of apparatus is discussed.

The study of sediments in marine environments has proceeded largely from the viewpoint of the physical conditions of deposition of the sediment. Particular attention has been paid to the study of marine sediments as composites of sizes, shapes, and mineral constituents acted upon by various components of a complex marine environment. Beach deposits, as a particular type of marine sediment, have been studied in this fashion with some success; however, many investigators have felt that a more fruitful approach in this case could be made from consideration of the dynamics of the sediment transportation and deposition system. The chief dynamic characteristic to be studied is the settling velocity, which is a function of the particle size, shape, surface texture, and density, and the fluid density and kinematic viscosity. A useful adjunct in such study is knowledge of the still-water settling velocity characteristics of the sediments in beach deposits.

Devices for determining settling velocities of discrete particles, as well as populations of particles, in the smaller size ranges (silt and clay) have been developed; but no satisfactory apparatus for simple, rapid determination of the settling velocities in still water of large sediments has been available. This paper describes an apparatus developed at the Beach Erosion Board by the author to make settling velocity analyses of sediments in the sand-size range.

Theory of manometric settling velocity tube--Consider a population of particles whose settling velocities in still water vary between v and v_n, and assume that all particles of the population are introduced without disturbance into a vertical still-water settling tube at the same instant. The tube cross-section is considered to be sufficiently large that each particle will fall at its true terminal velocity after some short period of acceleration. Some time after introduction the particles will be segregated vertically in the order of their settling velocities, the slower particles at the top and the faster at the bottom of the column. Once this segregation is obtained the terminal velocity of fall, or settling, of any fraction of the population may be determined by timing its passage between known points.

The identification of a particular fraction of the population at two known points may be achieved simply by measuring the variations in pressure at these two points and relating the variations on a common time base. Computation of the settling velocity of the various fractions furnishes the data required. We may show this to be the case as follows.

Let us consider a tube, filled with still water, and provided with two pressure points P_1 and P_2, as shown in Figure 1. The length of the tube from the level of introduction of the material to the uppermost pressure point is prescribed to be sufficient for all particles to have become segregated in the order of their respective terminal velocities.

Before the introduction of particles in the tube the expressions for pressure at points P_1 and P_2 are

$$P_1 = \gamma_w (H - h)$$

$$P_2 = \gamma_w H$$

$$\Delta p = P_2 - P_1 = \gamma_w h$$

where γ_w is the specific weight of the water, H is the depth of pressure point, P_2, below the surface, and h is the vertical distance between pressure points P_1 and P_2. After the sample has been introduced and the particles allowed to reach their terminal velocity but before any particles have settled to point P_1, the pressure expressions are

$$P_1 = \gamma_w (H - h) + \gamma_s V/A$$

$$P_2 = \gamma_w H + \gamma_s V/A$$

$$\Delta p = \gamma_w h$$

where γ_s is the specific weight, and V is the volume, of the added particles. The cross sectional area of the settling tube is A.

The additional pressure attributable to the particles, $\gamma_s V/A$, is divided into, an increase in water level $\gamma h = \gamma_w V/A$, due to the displacement of the added material, and the unbalanced weight $W = (\gamma_s - \gamma_w)V/A$ of the material. Since the material added to the system remains in the tube, H must be added to H and (H - h) in the expressions above, giving

$$P_1 = \gamma_w (H - h + \delta H) + W \quad \text{. . . . . (1)}$$

$$P_2 = \gamma_w (H + \delta H) + W \quad \text{. . . . . (2)}$$

$$\Delta p = \gamma_w h \quad \text{. . . . . (3)}$$

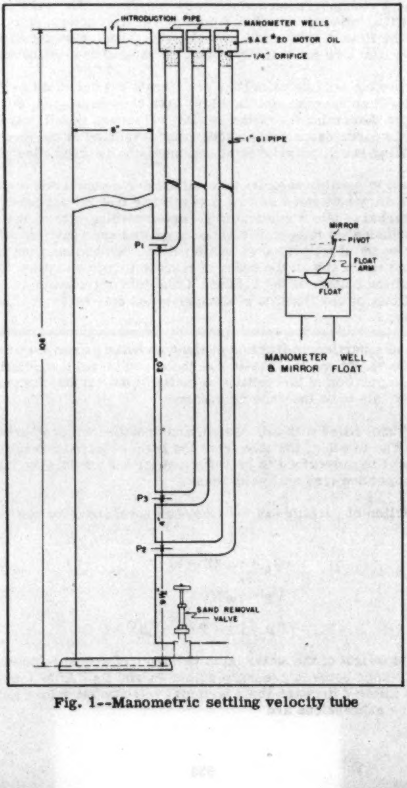
INTRODUCTION PIPE
MANOMETER WELLS
S.A.E. #20 MOTOR OIL
1/4" ORIFICE
8"
1" GI PIPE
108"
P1
80"
P3
4"
P2
3½"
SAND REMOVAL VALVE
MIRROR
PIVOT
FLOAT ARM
FLOAT
MANOMETER WELL & MIRROR FLOAT

Fig. 1--Manometric settling velocity tube

Suppose that the particles having the highest settling velocity, v, represent a fraction, w_1, of the total population introduced. These particles will pass pressure point P_1 at essentially the same instant. Immediately the pressure contributed by this fraction of particles is subtracted from the P_1 pressure of (1) and we have

$$P_1 = \gamma_w (H + \delta H - h) + (W - w_1) \quad \text{.................... (1a)}$$

$$P_2 = \gamma_w (H + \delta H) + W \quad \text{.......................... (2a)}$$

$$\Delta p = \gamma_w h + w_1 \quad \text{.......................... (3a)}$$

These pressure relations are shown on Figure 2.

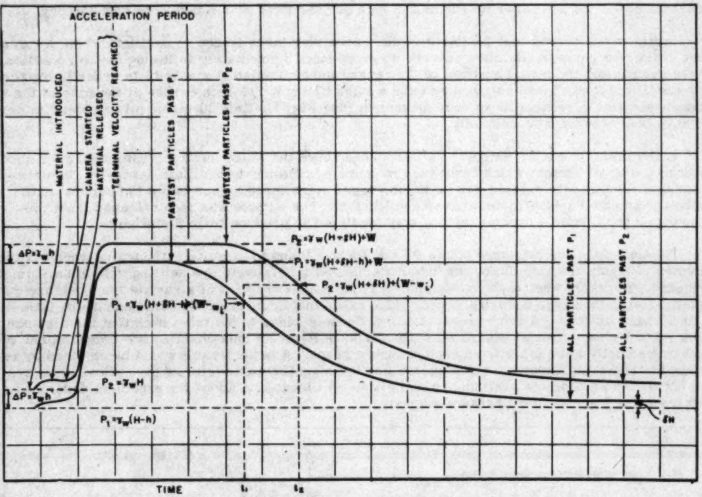

Fig. 2--Pressure relations during settling

It is apparent that the settling velocity of any fraction w_1 can be determined by identifying the pressure associated with w_1 on the P_1 and P_2 curves, measuring the time interval between these points, and dividing the distance, h, by the time interval.

Since the pressure effects of the total sample appear in the pressure diagram, a simple linear division of the total pressure difference $[\gamma_w (H + \delta H - h) + W] - [\gamma_w (H - h)]$ corrected by the subtraction of δH, provides a measure of the frequency distribution. It is therefore not necessary to weigh the sample.

Having computed from the pressure diagram the settling velocities of a suitable number of fractions of the total sample various graphical presentations of the data are possible. It should be noted, however, that preparation of graphs is not necessary, since the pressure diagram itself is an adequate graphical record of variations in settling velocity. Maximum and minimum settling velocities as well as quartile, median, or other fractional velocities may be computed directly from the pressure diagrams.

The apparatus--An experimental settling velocity tube built at the Beach Erosion Board is shown schematically in Figure 1. The tube is a section of six-inch inside diameter steel pipe, 106 inches long, with its bottom end capped by an ordinary iron pipe cap; this cap is fitted with a two-inch gate valve to permit draining and cleaning the pipe. Pressure taps for one-inch pipe manometers are located as shown. The size and length of the tube were fixed arbitrarily by considerations of convenience, and the time required for particles to reach terminal velocity. No attempt was made to determine the optimum diameter and length of tube to insure complete segregation of the particles and freedom from particle interaction, this being left for future work.

Each pressure point is connected by a one-inch galvanized iron pipe to an open manometer well located at the normal water surface elevation. A schematic sketch of the manometer is shown on Figure 1. Motion of the manometer liquid surface during the test is transmitted through a hemispherical cork float and lever system to a mirror. Light falling on the mirror from a small source is employed in an optical lever system, through rotation of the mirror by changing liquid level, to record the liquid level variations photographically on sensitized paper. A slotted disc, driven at constant speed, interrupts a light beam to provide a time scale on the record. Time intervals of 0.2 sec and paper speeds of 1/2 inch per sec have been found to be satisfactory.

Initial trials showed that the liquid in the manometer tubes tended to oscillate whenever pressure changes occurred. Oscillations were so pronounced immediately following the introduction of the sample that the initial portions of the record were completely masked. In order to overcome this condition, it was found necessary to use a light oil and a 1/4-inch orifice at the base of the manometer well to reduce the surface movement (see Fig. 1). SAE 20 motor oil and clear mineral oil have both been used successfully.

In the initial trials the sample was introduced above the water surface. This created a shock wave in the liquid system which caused the manometer columns to oscillate severely. To overcome this condition the sample was first submerged some three inches below the surface until saturated and the liquid system attained equilibrium. The sample was then released from this submerged position by a special release trap, designed to produce little disturbance.

The use of the two pressure points P_1 and P_2 was found to be quite satisfactory when testing samples of material which did not include materials with relatively low settling velocities, namely, fine sand. However, when both coarse and very fine sand were part of a sample the pressure curves were so flat in the range covering the very fine sands that accurate determinations of the time interval were difficult. A third pressure point, P_3, was added to the tube, such that the distance from P_2 to P_3 was small as compared to the distance P_1 to P_2 thus enabling two computations of the same velocity to be made from each pressure graph. A better result would be obtained by reducing the recording paper speed, or increasing the magnification factor of the optical lever system but for the purposes of preliminary tests it was preferable to adopt the expedient described. Figures 3 and 4 are sample pressure diagrams.

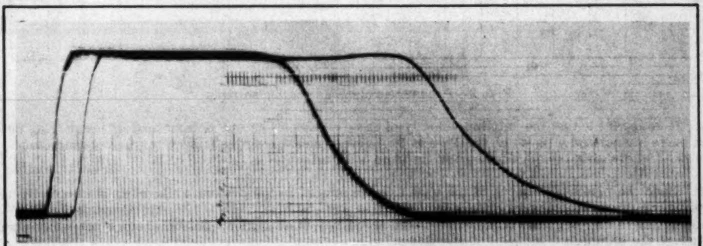

Fig. 3--Manometric settling velocity tube pressure diagram

Typical results--Figures 5 and 6 are typical cumulative frequency-settling velocity curves for two natural beach sands. Each original sample was split into approximately four 36-gram samples and each portion tested. The various symbols on the figures identify the test results from each portion. The curves serve to illustrate the range of velocities which can be covered.

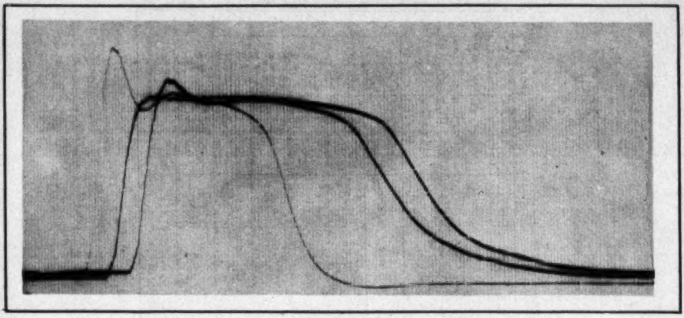

Fig. 4--Manometric settling velocity tube pressure diagram

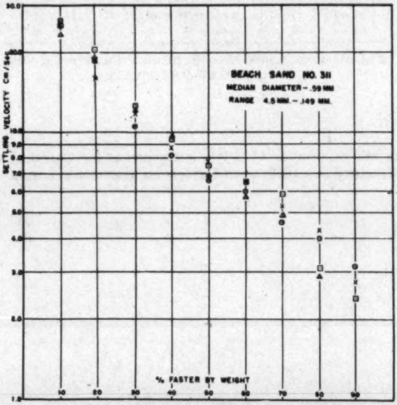

Fig. 5--Beach sand No. 311; median diameter, 0.59 mm; range 4.5 mm-0.149 mm

Future developement--It is apparent that further development of the apparatus is required; this report is made at this time solely to encourage such development as may be desirable for the various applications to which it is suited. Particularly to be studied are the instrumentation problems of (1) the optimum tube sizes for various size ranges and characters of material; (2) means of introducing material into the tube; and (3) refinement of the recording system. However, it is believed that the manometric settling velocity tube whose principle of operation is outlined above will provide a simple, quick, accurate means of determining the settling velocities of sediments.

Acknowledgment--The author acknowledges the valuable contribution of Eugene A. Dedick, who performed many tests and suggested the use of the oil orifice damping system on the manometers to reduce oscillation.

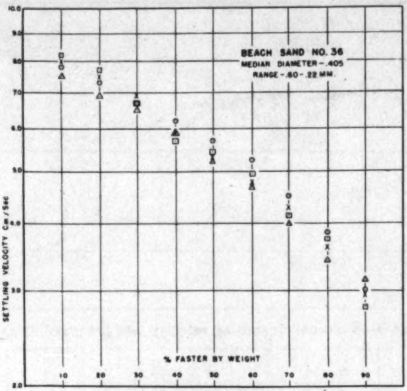

Fig. 6--Beach sand No. 36; median diameter, 0.405; range 0.60-0.22 mm

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Washington 25, D. C.

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ARTIFICIAL RECHARGE OF GROUND WATER BY THE CITY OF BOUNTIFUL, UTAH

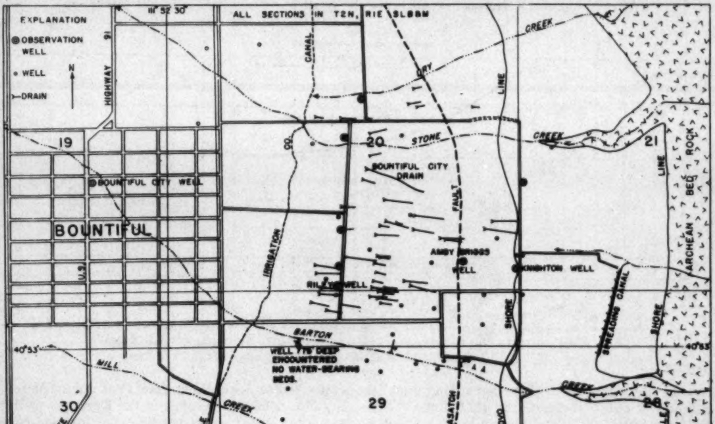
H. E. Thomas

(Published by permission of the Director, U. S. Geological Survey)

Abstract--The City of Bountiful, Utah, is situated just beyond the eastern edge of an area where alluvial gravel and sand of Pleistocene and probably Tertiary age yield water by artesian flow. Attempts to recharge these aquifers by diversion of surplus stream water into a spreading canal east of the city have been unsuccessful, because of the relative impermeability of the torrential debris which has accumulated along the western base of the Wasatch Range. Instead, the water spread from the canal has increased the yield of permeable shore deposits of the Pleistocene Lake Bonneville which crop out east of the city.

The City of Bountiful, located at the west base of the Wasatch Range about eight miles north of Salt Lake City, has increased in population to the point where existing water supplies from wells, springs, and streams are inadequate to meet the summer demand. The city lies near the eastern edge of a natural ground-water reservoir, formed by Pleistocene beds of pre-Lake Bonneville age, which is tapped by hundreds of wells. Most of these wells yield water by artesian flow for irrigation, but there are also numerous domestic wells and several industrial wells, some of which flow and some of which are pumped. The quantity of water yielded annually by these wells is a large proportion of the perennial safe yield of the reservoir.

In recent years the City of Bountiful has endeavored to increase the storage of water in this artesian reservoir by artificial recharge from a canyon stream during the non-irrigation season, with the intention of constructing wells to divert this stored increment into the municipal water system during periods of peak demand. Since 1941 a part of the flow of Barton Creek has been diverted into a spreading area north of the stream channel and south of the channel of Stone Creek (see Fig. 1). The spreading canal is about 5000 ft above sea level and about a quarter of a mile


EXPLANATION
OBSERVATION WELL
WELL
DRAIN
N
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111°52'30"
ALL SECTIONS IN T2N, R1E SLB&M
CANAL
DRY
CREEK
LINE
19
20
21
STONE
CREEK
BOUNTIFUL CITY WELL
BOUNTIFUL CITY DRAIN
BOUNTIFUL
U.S.
IRRIGATION
FAULT
AMBY BRIGGS WELL
KNIGHTON WELL
RILEY WELL
SPREADING CANAL
SHORE
ARCHEAN BED ROCK
BARTON
WELL 775' DEEP ENCOUNTERED NO WATER-BEARING BEDS.
40°53'
MILL
CREEK
30
29
28
WASATCH
PROVO
BONNEVILLE
ALTERNATE
TO SALT LAKE CITY 8 MILES
SCALE
0 1000 2000 3000 4000 5000 Feet

Fig. 1--Spreading canal, wells, and water tunnels east of Bountiful, Utah east of the Provo shore line of the Pleistocene Lake Bonneville, which has an altitude of about 4800 ft above sea level. The canal is about 1200 ft long, and water flows through 11 outlets into an area covered by oak brush. The oak-brush area is highly absorptive, and there has been no evidence of silting up in several years of water-spreading operations. The quantities of water diverted each year are set forth in Table 1, based on weir measurements made in 1946 and 1947, and on estimates for prior years.

Table 1--Artificial recharge by the Bountiful spreading canal

Year	Period of diversion	Quantity diverted	
		ac ft	million gal
1941	May-June 5	75	24.4
1942	April 14-June 18	180	58.7
1943	April 14-May 13, June 5-18	130	42.3
1944	January-May	300	97.7
1945	February 9-May	400	130.3
1946	February 20-June 10	450	146.6
1947	February 21-June 5	425	138.4

The water spreading caused a marked rise of water level in wells within half a mile west from the spreading canal. This marked rise was clearly due to the water spreading rather than to natural recharge from streams or other sources because it occurred only in wells down the slope from the spreading canal. In wells that tap the same geologic formations at comparable altitudes, but south of Barton Creek or north of Stone Creek, the water levels changed very little from season to season; or, in wells where the range in seasonal fluctuations of water levels exceeds one or two feet, the fluctuations were markedly different from those in the wells west of the spreading canal, and were directly traceable to irrigation or precipitation upon adjacent land, or to seepage from nearby stream channels.

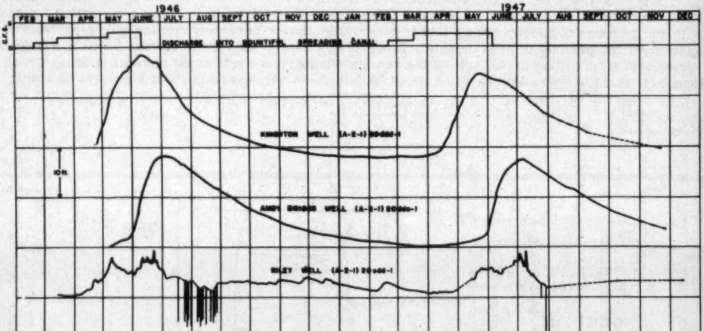

Fig. 2--Hydrographs of several wells and drains, showing effect of recharge from spreading canal (for locations, see Fig. 1)

In the wells nearest the spreading canal the water levels rose more than 15 ft during the periods of water spreading in 1946 and 1947 (see Fig. 2). The water level in the Knighton well, 1750 ft west of the canal, began to rise about 40 days after water was first diverted into the canal, indicating an average rate of movement from canal to well of about 45 ft per day. West of that well the hydraulic gradient and the rate of movement were somewhat less. In the Amby Briggs well, 1000 ft west of the Knighton well, the water level began to rise about 45 days later than in the

Knighton well. Both these wells obtain water from the permeable shore gravels of the Provo stage of the Pleistocene Lake Bonneville. In the vicinity of the Amby Briggs well and farther west, numerous water tunnels and drains tap the shore deposits and yield water for irrigation and domestic use. The discharge of many drains and tunnels has increased appreciably in recent years; as an example, in the summer of 1947 the rate of discharge of a tunnel owned by Bountiful City was more than twice as much as in summers prior to the beginning of water-spreading operations. It is evident that the water spread by the City of Bountiful has served chiefly to increase the yield of these drains, for in wells farther west the observed fluctuations of water level are small and not clearly attributable to the water spreading. In the Riley well, 2300 ft west of the Amby Briggs well, a slight rise of water level during September of each year may be due to artificial recharge, but it might instead be caused by cessation of pumping or by other factors.

There is no evidence that the water spreading has resulted in increased storage in the deep-lying reservoir. Throughout the area of artesian flow the major fluctuations in artesian pressure are due to discharge from wells, and the effects of seasonal recharge cannot be discriminated. In wells penetrating the artesian reservoir east of the area of artesian flow, however, fluctuations of water level show clearly the effect of recharge from streams and from water applied for irrigation. These fluctuations show that the recharge to the artesian reservoir occurs chiefly during the spring freshets in the canyon streams, and during the summer when water is pumped from the Jordan River for irrigation of lands near the City of Bountiful. The principal recharge area for the artesian reservoir is below an altitude of 4600 ft, three quarters of a mile west of the spreading canal and more than a mile west of the eastern limit of the valley fill. This condition in the vicinity of Bountiful contrasts with that in most of the intermontane basins of the West, where the coarsest and most permeable sediments commonly adjoin the mountain ranges and constitute the recharge areas for the aquifers of the valley fill.

The explanation for these exceptional conditions in the vicinity of Bountiful lies in the character of the valley fill, which is the unconsolidated gravel, sand, and clay beds which have accumulated to depths of hundreds and even thousands of feet in all lowland areas between the mountain ranges of the Great Basin. This process of accumulation, which is continuing at the present time, is almost entirely the product of stream action, including erosion of the mountain areas, transportation down steep slopes in the canyons, and deposition in the valley areas beyond the mouths of the canyons. The rate of accumulation is not uniform, but varies with the volume of stream flow. Much debris is carried to the valleys during the spring freshets when streams are swollen by the melting of snow. Even greater quantities of debris may be moved during floods caused by high-intensity rainstorms, which are common in this region during the summer. The alluvial deposits generally are poorly sorted, but the larger perennial streams commonly achieve better sorting than small or intermittent streams, and the torrential debris from cloudburst floods is least sorted of all.

In this region of highland erosion and torrential deposition in the lowlands, the Bountiful area has several distinctive features. The debris eroded from the Wasatch Range here contains a large proportion of clay, the product of long weathering of the pre-Cambrian gneisses and schists that form the range.

Deep residual soils in the mountains have been formed during past geologic ages. This clay, together with angular fragments of all sizes, constitutes the material that is eroded from the mountains and transported to the valleys. Cloudburst storms produce the spectacular and devastating mud-rock flows which have occurred in several streams in the vicinity in recent years. These are viscous masses that roll slowly down the stream channel like wet concrete. Recent movement along the Wasatch Fault (see Fig. 1) along the base of the range has resulted in increased stream gradients in the lower parts of the canyons, with the result that these viscous mud-rock flows, once started in the mountain area, are likely to continue down the canyon and come to rest west of the fault line. Torrential deposits have accumulated over a belt one to three miles wide west of the fault since the recession of Lake Bonneville. These torrential deposits are unsorted, and because of the high proportion of clay they are far less permeable than the torrential debris in many other parts of the Great Basin.

Well logs show that impermeable torrential debris has been accumulating in this belt for a comparatively long period of geologic time. One well east of Bountiful (see Fig. 1) reached a depth of 775 ft, and penetrated a total thickness of 735 ft of unsorted debris of torrential origin, consisting of angular fragments of all sizes in a clay matrix. This material was so impermeable that the well did not yield even enough water for drilling operations. Other well logs show that unsorted torrential debris predominates in a belt one to two miles wide west of the Wasatch Fault, and that materials carried farther west by the larger streams are commonly better sorted. It is this better-sorted material, deposited west of the mud-flow materials, that makes up the water-bearing beds of the artesian reservoir. The deposition of unsorted alluvial material was interrupted during the rise and recession of Lake Bonneville, when well-sorted shore deposits and lake-bottom sediments were accumulated. The lacustrine deposition, however, represents only a small fraction of the total amount of valley fill. These well-sorted deposits occur near the top of the valley fill, but have been covered thinly in many places by torrential deposits since the recession of the lake.

The water spread by the City of Bountiful moved westward through post-Lake Bonneville alluvium and Lake Bonneville shore deposits, until it reached the permeable shore materials of the Provo stage, whence most of it was discharged from water drains and tunnels. The underlying pre-Lake Bonneville deposits of torrential origin are sufficiently impermeable that very little if any water moved westward through them to the artesian aquifers farther west. It is concluded that, where artificial recharge is for the specific purpose of storing water that is to be diverted subsequently from a certain aquifer by means of wells, it is essential that proof be obtained that the water does reach that aquifer. This proof requires an adequate knowledge of the geologic and hydrologic conditions, supplemented by detailed observations of the effects of the artificial recharge. The City of Bountiful wisely made provisions for obtaining this evidence, and thus has a basis for modifying its program of artificial recharge or ground-water development to serve its needs best.

U. S. Geological Survey,
Salt Lake City, Utah

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COMPUTING SOIL TEMPERATURES

Walter B. Langbein

Abstract--This paper develops a method for computing temperatures at a point in a soil from surface temperatures. The method is adaptable to the irregular fluctuations in temperature ordinarily found in nature as well as to ideal cases. The temperature at a point in the soil is expressed as a weighted function of antecedent temperatures at the surface. An analogy is made with the unit hydrograph, a familiar tool in hydrologic practice.

The analysis of the flow of heat through isotropic solids is perhaps one of the classics of mathematical physics. It is difficult to add materially to the analysis and solution of this problem. However most of the examples ordinarily used to explain the flow of heat present rather simplified problems. A common exercise in the texts in the field of geophysics is to show how the diurnal or the annual temperature cycle, represented by a sine curve, is reduced in amplitude and lagged in time with depth in the soil. Soil temperatures rarely conform to this ideal. It would be impracticable to write a formal mathematical expression for the day to day fluctuations in temperature. A method is suggested for expressing the variation in soil temperature as a weighted mean of antecedent temperatures, based on Fourier precepts; adaptable to the ideal case as well as to the erratic fluctuations found in nature.

The first postulate is that the temperature at a point in the soil is the net resultant of the action of all antecedent temperatures each acting independently of the other. This statement involves the principle of superposition mentioned by BATEMAN [1944], and may be used to obtain particular solutions of certain linear differential equations, such as the familiar heat-flow equation $\partial\mu/\partial t = \alpha(\partial^2\mu/\partial x^2 + \ldots\ldots\ldots\ldots)$. The principle of superposition seems adaptable to the simplification of otherwise complex situations involving heat or ground-water flow.

The variation in temperature at a point in the soil induced by a heating of the surface to a temperature θ_s above the initial temperature at that point is given by the integral [INGERSOLL and ZOBEL, 1913, Chap. 7],

$$(\theta - \theta_s)/(\theta_0 - \theta_s) = (2/\sqrt{\pi}) \int_0^{x/2\alpha\sqrt{t}} e^{-\beta^2} d\beta \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where θ_s is the temperature at the surface, θ_0 is the initial temperature of the soil, θ is the temperature at a depth x at time t measured from the beginning of temperature θ_s, α is the square root of the thermal diffusivity, and β is the variate $[x/(2\alpha\sqrt{t})]$. The quantity under the integral sign will be recognized as the probability function. Figure 1 is a graph of this definite integral in terms of time.

Consider the graph of temperature at a depth x induced by surface heating to a temperature θ_s for a unit of time. For an example, let us suppose soil at a uniform temperature of 50° and the surface is heated to a temperature of 60° beginning with time zero. The temperature at a depth x in the soil will increase from 50° to 60° at a rate according to Figure 1. Now on this same system let us superpose a surface temperature of 40° beginning a unit of time later. Acting alone the effect would be a lowering of temperatures in the soil from 50° to 40° in the same manner as on Figure 1. If the two temperature systems act together the surface temperature would be represented by a bar graph rising from 50° to 60° at time zero and continuing at 60° to time 1 and then returning to 50°. The temperature at depth x in the soil would be represented by a rise above 50° to a peak lower than 60° and a slower return to the initial temperature of 50°. This variation is illustrated in Figure 2, and is computed by simple displacement of the graphs of temperature shown on Figure 1 by the duration of the temperature rise, which is one unit of time in Figure 2. The procedure here outlined is quite similar to the well recognized technique of the "S" and unit hydrographs as applied to stream-flow synthesis [SHERMAN, 1932].

Figure 2 shows the time variation in temperature at a point due to a surface heating (or cooling) of unit duration. It may also show the respective proportional effects of variable surface heating during units of antecedent time. From this viewpoint, the temperature at a given time in the soil is

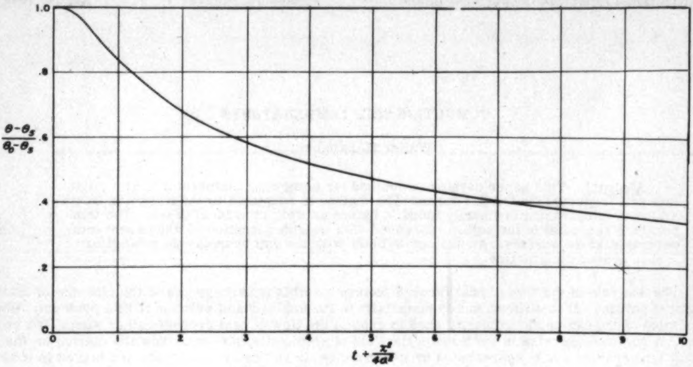

Fig. 1--Graph of Equation (1)

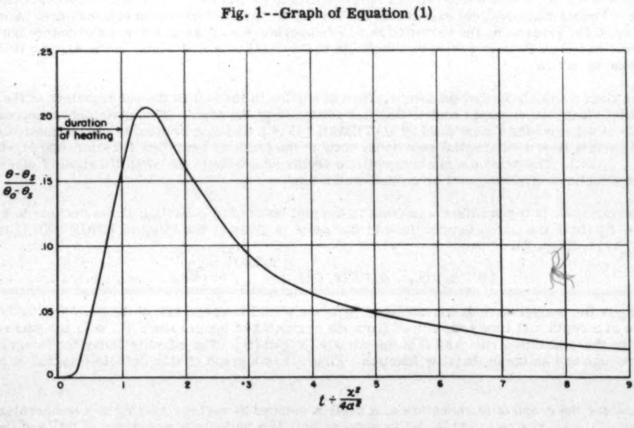

Fig. 2--Effect of surface heating to temperature θ for a unit period on the temperature at depth x in respect to time t

composed of the several fractions of the antecedent temperatures weighted according to Figure 2. Surface temperatures antecedent to the fourth period have virtually no effect.

By way of illustration and verification we might apply the method to the simple case of surface heating according to a sine curve (see Fig. 3). The problem is to compute temperature at a depth of 240 cm.

The value of the diffusivity α^2 is taken as 0.0028 in cgs units, the time unit is therefore $(240\ \text{cm})^2 / 4 \times 0.0028 = 5{,}250{,}000$ sec = 2 months. One month therefore corresponds to 0.50 time units. The probability integral (see Fig. 1) read off at these intervals is listed in the second column of Table 1 and the identical values are listed in the third column offset by a month expressed in time units as above. The last column lists differences between the third and second column. The differences listed in the last column are the weights or coefficients giving the distributive effect of a month's

Table 1--Distribution coefficients from probability integral for depth of 240 cm

Time	$(q)_t$	$(q)_{t-0.5}$	Distribution coefficients
0	1.000	1.000	0
0.5	0.954	1.000	0.046
1.0	0.843	0.954	0.111
1.5	0.752	0.843	0.091
2.0	0.683	0.752	0.069
2.5	0.629	0.683	0.054
3.0	0.586	0.629	0.043
3.5	0.551	0.586	0.035
4.0	0.521	0.551	0.030
4.5	0.495	0.521	0.026
5.0	0.473	0.495	0.022
5.5	0.453	0.473	0.020
6.0	0.436	0.453	0.017
6.5	0.421	0.436	0.015
7.0	0.407	0.421	0.014
7.5	0.394	0.407	0.013
8.0	0.383	0.394	0.011
8.5	0.372	0.383	0.011
9.0	0.363	0.372	0.009
9.5	0.354	0.363	0.009
10.0	0.345	0.354	0.009
10.5	0.338	0.345	0.007
11.0	0.330	0.338	0.008
11.5	0.323	0.330	0.007
12.0	0.317	0.323	0.006
			0.683

mean temperature at a depth of 240 cm. These distributive coefficients are applied to the monthly mean temperatures and summed very much as in unit-hydrograph techniques. The resultant graph of temperature is identical with that computed directly from the equation for simple periodic flow [INGERSOLL and ZOBEL, 1913].

$$\theta = \theta_0 \, e^{-(x/\alpha)\sqrt{\pi/T}} \sin[2\pi t/T - (x/\alpha)\sqrt{\pi/T}] \ldots\ldots\ldots\ldots\ldots (2)$$

It is quite evident that the variate, $x^2/4\alpha^2$ is uniquely related to the lag and to the reduction in amplitude of a simple periodic wave,

$$\left.\begin{aligned} x^2/4\alpha^2 &= T/4\pi(\log_e r)^2 \\ x^2/4\alpha^2 &= (\pi/T)\text{lag}^2 \\ \text{lag} = T(-\log_e r)/2\pi &= T\,[\log_e(1/r)]/2\pi \end{aligned}\right\} \ldots\ldots\ldots\ldots\ldots (3)$$

where T is the period of the wave, and r is the ratio of the amplitude or ranges, of temperature at the lower to the upper depth.

As a simple demonstration of the application of a distribution graph to abrupt changes in temperature, suppose that a uniform period of ground temperature of 0°C is broken by a four-day rise in temperature to 10°C, followed by a return to the original 0°C. What are the temperatures at a depth of 100 cm, if the thermal diffusivity (α^2) is 0.011 cgs units? The solution is given as follows.

Period of heating = 4 days = 345,600 seconds; value of
$x^2/4\alpha^2$ = 228,000 seconds = 2.65 days

The values of the probability interval (see Fig. 1)are listed at two-day intervals in Table 2.

The first column shows the time in days, the second in terms of the variate $t \cdot 4\alpha^2/x^2$.

The third column lists values of q_t from Figure 1 and the fourth, values of q_t offset by the

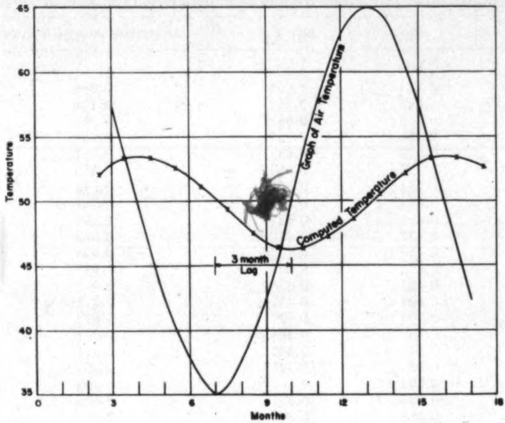

Fig. 3--Equivalence of results obtained by use of Figure 1 and Equation 2 for the case of a simple sine curve

period of heating four days or 1.5 in terms of the variate $t \cdot 4\alpha^2/x^2$.

Table 2--Distribution coefficients and computed temperature increase at a depth of 100 cm

Time		q_t	$q_{t-1.5}$	Distribution coefficients	Rise in temperature
Days	Variate				°C
0	0	1.000	1.000	0	0
2	0.75	0.898	1.000	0.102	1.02
4	1.5	0.752	1.000	0.248	2.48
6	2.25	0.654	0.898	0.244	2.44
8	3.0	0.586	0.752	0.166	1.66
10	3.75	0.534	0.654	0.120	1.20
12	4.5	0.495	0.586	0.091	0.91

The fifth column lists the differences between the fourth and third columns and represents the distributive effect of a four-day change in temperature at the surface applicable at a depth of 100 cm. The rise in temperature is listed in the final column and is computed by simply multiplying the distribution coefficients by the total rise in temperature at the surface; 10° C is this example.

To continue the example, let us suppose that the four-day period of heating to 10°C was immediately followed by a four-day period of heating to 20°C, then return to 0°C. What are the resulting temperatures at the depth of 100 cm? The answer is directly obtained from the distribution coefficients computed in the fifth column of Table 2 as shown in Table 3.

This table lists the temperature due to the first period of heating and the temperature rise due to the second period of heating. The final column lists the total heating effect in this case.

The value of the distribution graph is its flexibility and adaptability to irregular variations in temperature. Figure 4 shows a record of soil temperatures published by BLISS [1944].

The graph shows observed and computed temperatures at four-foot depth, based on a value of $x^2/4\alpha^2$ of 7 days. Deviations probably reflect the effect of changes in thermal diffusivity produced

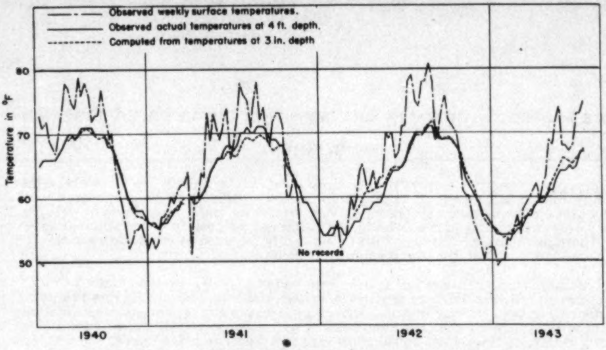

Fig. 4--Comparison of observed and computed temperatures at a depth of four feet using Bliss' data

Table 3--Temperature increase at a depth of 100 cm with two increases in surface temperature 4 days apart

Time	Partial change		Total change
	10°	20°	
day	°C	°C	°C
0	0	0	0
2	1.02	0	1.02
4	2.48	0	2.48
6	2.44	2.04	4.48
8	1.66	4.96	6.62
10	1.20	4.88	6.08
12	0.91	3.32	4.23

by changes in soil moisture. Nevertheless the conformance is sufficiently close to suggest that the record of soil temperatures at depth could be extended on the basis of air or surface soil temperatures.

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SOME PROPERTIES OF WATER SOLUTIONS THAT INFLUENCE INFILTRATION

Joel E. Fletcher

Abstract--Poiseuille's approximation was modified to include the case where the solution in the capillary ends in an air-water interface instead of the usual large volume of water. Such factors as surface tension, viscosity, pore size, depth of wetting, head of water, wettability of the solid by the solution, and density of the solution appear in the resultant equation. Temperature is indirectly included in the equation since it enters into values of both surface tension and viscosity.

The relationships between infiltration rate and each of the various factors in the equation are as follows: Surface tension increases linearly with infiltration rate; viscosity decreases hyperbolically with infiltration rate; pore size increases infiltration rate parabolically; depth of wetting and head of water decrease infiltration rate hyperbolically; wettability increases infiltration rate in a skewed cosine curve; and temperature increases infiltration rate linearly. Brief experimental evidence was included to support the equation.

This paper points out the need for further research on the infiltration of solutions into dry soils and suggests directions that this research might take.

Several properties of solutions have long been recognized as affecting the permeability of soils to these solutions. It has been generally assumed that these factors have similar effects on infiltration into dry soils. It is the purpose of this paper to point the way to further investigations of the factors affecting both permeability and infiltration as well as to point out those factors which affect only infiltration into dry soil.

A number of investigators have studied the movement of water in soils. SLATER [1948] outlined some of the forces operating and their effects on water movement under high-moisture conditions. It would seem, however, from the available literature that dry soils have been largely neglected. The comments that follow will be specifically and almost entirely directed toward soils either in the dry state or nearly so.

If we assume that soils are made up of more or less cylindrical capillaries as in Figure 1, we may use Poiseuille's approximation:

$$Q = \pi r^4 P/8L\eta \quad \text{.........................(1)}$$

if the capillary again opens into free water at h. In (1) r is the radius of the capillary of length L. η is the coefficient of viscosity. P is the pressure driving the water through the capillary, and Q is the rate of flow.

If the capillary below h is continuous and filled with air, then P may be evaluated in terms of its capillary and gravitational components. $2\pi\gamma r\cos\theta$ is the force due to capillarity where γ is the surface tension and θ is the angle θ in Figure 1 made by the contact of the liquid and capillary wall. In other words, θ is the wettability and would vary from 0 in perfectly wettable surfaces to 180° in non-wettable surfaces. The quantity $\rho\pi r^2 gh$ is the gravitational force component of P where ρ is the density of the liquid, r is the radius of the capillary, g is the gravitational constant, and h is the total length of the liquid column in Figure 1. Combining these two components and dividing by the area of the capillary we may write

$$P = \rho r g h + 2\gamma\cos\theta/r \quad \text{.......................(2)}$$

If we substitute (2) in (1) in place of P we get

$$Q = \pi r^3(\rho r g h + 2\gamma\cos\theta)/8L \quad \text{...............(3)}$$

Some or the properties of (3) are more readily seen if we convert these into customary units where Q is in surface inches and construct curves for the relation of Q to the other variables in turn. Let us assume that ρ is unity and g is 980 throughout. If we hold $h = L = 1$, with $\gamma = 72$, $\eta = 0.01$, and $\theta = 0$, then the relation between Q and r becomes the curve in Figure 2a. There is a rapid increase in Q as r increases in the range between 0.01 and 0.02. This is the critical size range mentioned by BAVER and FARNSWORTH [1940]. In other words, this is the range in pore sizes below which considerably greater amounts of energy must be expended to produce a unit of flow. Pores above this size range have been termed "non-capillary."

If values of γ, η, and θ are chosen as above and r becomes 0.01 with $h = L + 10$, the relation between L and Q can be seen from the curve in Figure 2B. This is the familiar curve for the relation of infiltration to time. It can also be seen from (3) that L increases with time. The familiar waves observed frequently in infiltration curves may possibly find an explanation in the stratification of the soil, since in fine-textured layers the water front moves more slowly than in coarse-textured layers, structure being equal. This in turn is reflected in values of Q.

If we again choose values of η, θ, h and L as in Figure 2A and r as in Figure 2B, the surface tension, γ, is seen to be related to Q by the straight line in Figure 2C. Popularly expressed opinions have been that since the main action of wetting agents was to decrease the surface tension, then reducing the surface tension should increase the infiltration rate, Q. That the converse of this is true is seen in Figure 2C. Experimental data showing that (3) is valid in this respect are given in Table 1. Solutions of known surface tension were added to Gila fine sandy loam soil and infiltration rates determined.

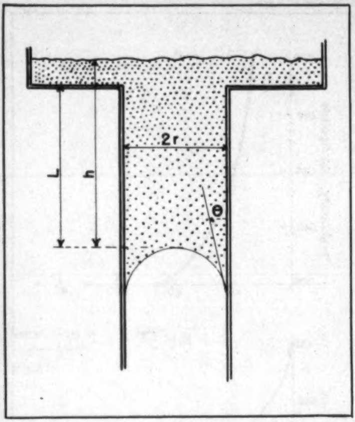

Fig. 1--Schematic diagram of an unsaturated soil pore, assuming it to be cylindrical and in contact with the vapor phase at the bottom

Table 1--The relation of infiltration of solutions in Gila fine sandy loam to surface tension and coefficient of viscosity

Treatment	Infiltration, Q	Surface tension, γ	Coefficient of viscosity, η
	in/hr[a]	dynes/cm	poises
Water, check	8.60	71.5	0.00837
Aerosol, 2 per cent	3.00	27.0	0.00872
Vinsol NVX 1 per cent	0.63	41.0	0.00965
Gelatin 0.2 per cent	6.90	52.0	0.00997
N-Calcium chloride	7.00	74.7	0.00873

[a] During the first hour.

Although the predicted relation of surface tension to infiltration can be seen to be operative, it is obvious that other factors are also at work.

If the usual values of γ, h, L, θ and r are chosen; viscosity, η, is seen in Figure 2D to be hyperbolically related to infiltration rate Q. It can also be seen in Table 1 that while infiltration may decrease both surface tension and viscosity fail to explain the values of Q found in Table 1.

The wettability or angle of contact between the liquid and solid phase, θ, is related to infiltration, Q, by the skewed cosine curve in Figure 2C. It can be seen that values of θ between 0° and 90° accelerate Q while those between 90° and 180° decelerate Q.

If we substitute the determined values of γ, η, and Q given in Table 1 into (3) and assume values of r and h of 0.04 and 1 respectively, the resultant equations may be solved simultaneously for θ.

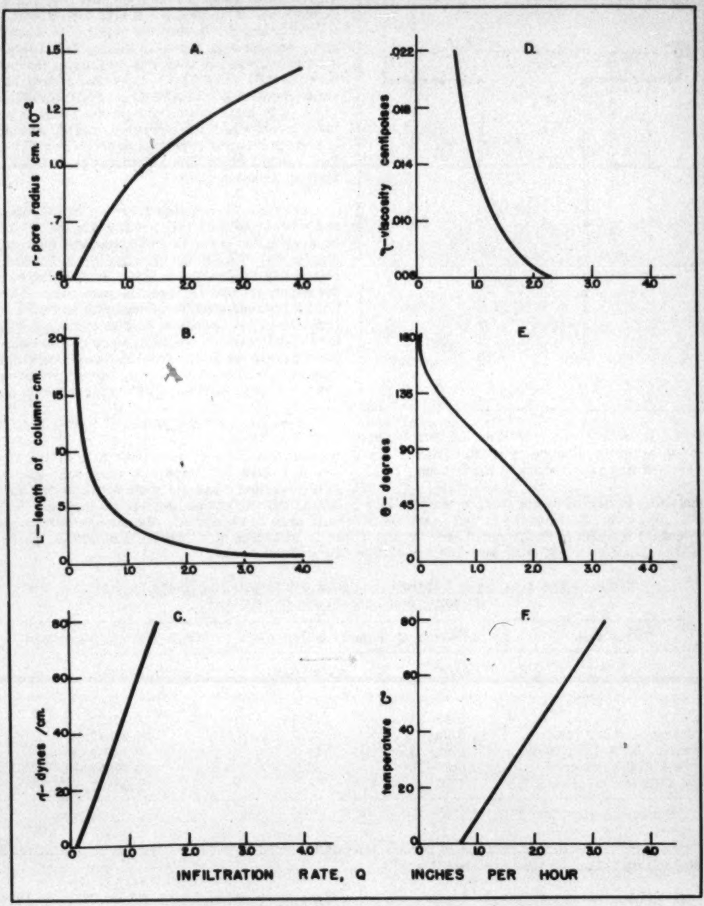

Fig.2--Curves showing the relation of the various components of (3) to infiltration rate, Q, while all other factors are held constant at the values given in the text

If we further assume that the smallest value of θ is 0, then the values of θ for the solutions in Table 1 become those given in Table 2.

The values for θ are seen to be reasonable and could offer an explanation for the behavior of these solutions on soil. This is particularly true in the case of Vinsol NVX and related compounds which though soluble in water prevent the soil from wetting. In this connection it is interesting to

Table 2--Calculated angle θ for the solutions in Table 1 assuming the angle for the 0.2 per cent gelatin solution to be zero

Solution	Angle of Contact, θ
	°
Water	39.3
Aerosol, 2 per cent	75.6
Vinsol NVX 1 per cent	160.8
Gelatin, 0.2 per cent	0.0
Calcium chloride 1 N.	59.0

note that with small heads, h, and fine capillary size, r, a solution of the nature of Vinsol NVX would actually retreat out of the soil against gravity. Such a performance has been noted following the forceful intrusion of the soil by this solution.

It can be seen that when h and L become large as they are in wet soils that both γ and θ are so reduced in their effects as to become negligible. It has been observed that under dry desert conditions certain soils, highly calcareous in the surface, have low infiltration rates. It is reported that similar soils under humid conditions take water readily. If this is true it may be explained by the wettability, θ,,since in the wet soil θ would be inoperative, while in the dry soil a large angle θ might seriously limit infiltration.

Surface tension, γ, and viscosity, η, are affected by temperature changes. If values for these properties at the different temperatures are substituted in (3), infiltration rate, Q, is seen in Figure 2F to bear a nearly straight line relationship to temperature. The importance and accuracy of this assumption is supported by the data presented in Figure 3. The scatter diagram is made up of values for the total amount of infiltration in inches taking place during the first 15 min after the beginning of rain from a type D-1 rainfall simulator. The temperature is the temperature of the surface three inches of soil at the beginning of rain. (Temperature of water and soil after rain, and temperature before rain all give similar results.) The soils involved are from all over southern Arizona and range in texture from sand to clay, and in age from recent alluvium to maturity.

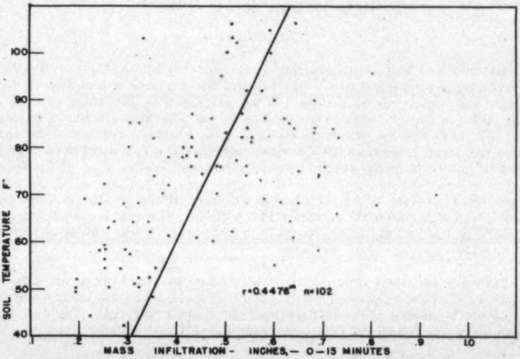

Fig. 3--Scatter diagram of soil temperature vs. mass infiltration for the first 15 minutes of rainfall for a large number of soils from southern Arizona

The simple correlation coefficient between temperature and infiltration is very highly significant ($r = 0.4476$, $n = 102$).

It would seem that several points regarding the properties of solutions affecting infiltration have been neglected to the extent that actual erroneous impressions have crept in. One of the more important of these seems to be the failure to differentiate between true wetting agents which affect the angle θ and surface tension reducers which affect only γ. It has been pointed out here that these actually have opposite effects on infiltration.

MARTIN and FLETCHER [1943] pointed out that the soils from the Mt. Graham area had a greater degree of aggregation in the winter than in the summer, yet, in spite of this greater aggregation, the soils in Figure 3 show a higher infiltration in the summer than in the winter. In all fairness, it should be pointed out that all of these soils showed such a high degree of dispersion that small differences in aggregation would not be expected to affect greatly the infiltration capacity.

The need for research on all of these questionable points except viscosity is obvious, at least so far as infiltration into dry soils is concerned. It is hoped that sufficient questions will be raised by this paper to stimulate effort and direct attention toward the great blank spaces in our information of the infiltration process.

Summary--The usefulness of Poiseuille's approximation to highlight some of the properties of solutions which affect infiltration has been pointed out. Brief experimental evidence has been presented to support the view that the use of this approximation may be valid and based on experimental fact.

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DISCUSSION

S. W. Jens (Horner and Shifrin, Consulting Engineers, St. Louis, Missouri)--This very interesting paper raises numerous questions in the mind of the engineer attempting to utilize the best current hydrologic knowledge. Does that part of the rainfall that infiltrates into the soil dissolve materials in the soil and rapidly acquire properties of the solutions discussed in this paper as affecting infiltration? Is one of the practical aspects of the analyses related to the applications of various solutions to extensive areas under irrigation? Has any research been done on the relation of the properties of solutions to the rate of recovery between applications of the solutions?

Figure 1 and Eq. (1) relate to the situation in which capillary tension is aided by gravity, with the further assumption of trapped air or vapor in the pores. It would be interesting to examine the various parameters of the Poiseuille approximation in relation to the ability of capillary forces to raise water from a free ground-water surface.

Table 1 is stated to be based upon infiltration rates determined for at least one hour. Can it generally be inferred that the relationships graphed in Figure 2 are the same irrespective of time on the curve from the beginning of the infiltration? It would also be of considerable interest to know how the solutions were applied to the Gila fine sandy loam; was a rainfall simulator used?

Plotting Q versus γ as given in Table 1, suggests that maybe the straight-line relationship of the equation is not supported by all of the data. Aerosol two per cent with γ of 27.0 has a Q of 3.00 but Vinsol NVX one per cent with a Q of only 0.63 has a higher ν of 41.0. In this case reducing the surface tension increased the infiltration rate. The few experimental data do not appear to be sufficient to support the theoretical conclusions.

The wettability explanation for the difference in infiltration rates of similar soils under desert and humid conditions leaves unanswered the thought that immediately arises: What factors resist the initial wetting of the dry soil, but have already conditioned the similar soil in the humid area? Would the dry soil never have the same wettability as the similar moist soil, even under prolonged application of water? If not, why not?

Fletcher's paper achieves the stated objective of suggesting specific additional information required for a better understanding of the infiltration process. It is hoped that fruitful research will also be stimulated by the paper and its discussions.

R. E. Uhland (Soil Conservation Service, Washington, D. C.)--The author's theoretical discussion, supported by a limited number of data, goes a long way toward explaining the complicated behavior of many soils. Some soils are difficult to wet and have very low infiltration rates, but when wetted the same soils take water rapidly. The manuscript points out the need for further research on many factors which are connected with infiltration.

It might be mentioned that numerous workers have studied and made many aggregation determinations and have shown, for example, that the degree of aggregation of the same soils may vary widely with the season. Few of these investigators, however, have been able to show any direct relation between aggregation and infiltration. For example, Fletcher found that some of the soils he studied showed greater aggregation in the winter than in the summer, but his measurements indicated higher infiltration in the summer. Obviously, the problem is very complex, but I believe that Fletcher's discussion has brought out some very excellent points and should stimulate further studies which will give more light on the subject.

M. R. Lewis (U. S. Bureau of Reclamation, Washington, D. C.)--This problem may be the essence of many of our field difficulties. It is suspected, though not backed by any experimental work, that the value of θ is the key to some puzzles.

Visual inspection of Figure 3 seems to raise considerable doubt of the "very highly significant" correlation of temperature and infiltration over the range of soils represented. I should, in fact, be greatly surprised if the temperature effect were great enough to overcome soil differences.

Joel E. Fletcher--Rainfall infiltrating into soil picks up soluble materials which affect its further infiltration into the soil. As a matter of comparison Vinsol NVX one per cent solution lowered the infiltration rate in Gila fine sandy loam to 0.63 in/hr (see Table 1) while mixing the soil with the same amount of Vinsol NVX only decreased the infiltration rate to 1.22 in/hr, indicating that perhaps only a portion of the material was in solution sufficiently to decrease the infiltration.

At the present time a large number of sundry products are being added to irrigation water to serve the express purpose of increasing its infiltration rate into the soil. It is not known whether these materials are actually effective nor is it known what the recovery rate or time between additions might be. It seems to me that this might be a very fruitful field for research.

Infiltration as I have used it in the paper is in terms of the total amount of water entering the soil from the surface from the time of its addition to the end of the first hour. It was added to the surface as an irrigation since it was hoped that the picture would be less complicated without the beating action of rain. As for the time factor in Figure 2, it was desired only to select a comparable time range for all of the vectors in Eq. (3).

Wettability is possibly a function of a large number of variables. It is known, for example, that once certain of the soil colloids are dehydrated they only rehydrate very slowly. It seems entirely possible, also, that certain colloids vary in their attraction for water. This should in turn appear in terms of their wettability.

V. S. Aronovici (Soil Conservation Service, Pomona, California)--Positive recognition of physical principles involved in water movement into and through the unsaturated soil independent of those affecting saturated flow is most important. Fletcher has clearly illustrated this fact by considering forces involved in water movement into dry soil.

The application of Poiseuille's principle to movement of water into a dry soil appears reasonable from a purely theoretical approach. From a practical standpoint, it is difficult to concede that soil pores are cylindrical or that the radius would have any degree of uniformity. Possibly, we are actually retarding progress in soil hydrology by attempting to apply directly physical principles developed for true capillary tubes. However, it is conceivable that the summation or averaging of all pores involved in any instant may produce resultant conditions described in this paper. Evidence presented suggests this to be the case.

A second assumption that the soil is dry at time of water entry is seldom true to fact, except in surface soil. It appears to the critic that the moisture content of soil when water applications are made will very strongly influence the value of the driving force, P, within the soil pores. In other words, the greater the potential gradient between water front and soil, the greater the rate of downward movement. The quantity of water required by dry soil to satisfy demand is generally inversely proportional to the mean radius of the pores. As water moves into the soil interstices, the capillary potential drops, thus reducing the value of P. It has been demonstrated in the field that initial intake rate into dry soil rapidly declines. When water application is stopped and later applied again, rates are essentially the same or slightly higher (never as high as the initial rate) than at the time it was turned off. It was concluded that such decline was due to falling gradients. Observed ratios between initial infiltration rates of sand and clay loam, for example, were 3:1 while coefficient of permeability ratio for the same materials was 2000:1. It is reasonably certain that larger pore radius of the sands made this very great difference in permeability, but it is doubtful that it was a primary factor influencing the narrow difference in infiltration rates.

For these reasons, it appears to be questionable logic to isolate any single principle of water movement into and through the soil and apply to actual conditons. Fletcher's discussion is still another link in the chain of factors involved that must be welded into the over-all picture. Unfortunately, he has not clearly defined the limitations of the forces involved in Poiseuille's principle. It is believed that Fletcher recognizes the limitations of the principles set forth; however, these limitations should be sharply defined.

The consideration of viscosity and surface tension as affecting infiltration is most timely. Results presented support conclusions derived from similar laboratory experiments with commercial detergents.

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PEDOLOGICAL RELATIONS OF INFILTRATION PHENOMENA

W. O. Smith

Abstract--An attempt is made to outline the principal features which are to be considered in infiltration problems. The need for consideration of genetic and morphological relations is emphasized, especially the view that the latter is a boundary condition for the quantitative procedures usually derived from the former. Detailed development of infiltration relations are given for the more usual genetic profiles. The role of soil structure in infiltration phenomena is developed in considerable detail. A discussion of fragmented soils is also given. A brief discussion of the physical mechanisms involved in infiltration develops the viewpoint that not only porosity and texture but also soil structure and moisture content are usually sufficient to define infiltration phenomena.

Introduction--Although soil genesis and morphology has been recognized for some time as a branch of soil science and although infiltration phenomena have been extensively studied, there is little in the literature of infiltration to show the importance of soil genesis and morphology in infiltration studies. In this paper an attempt will be made to evaluate, qualitatively, certain pedological aspects which it appears must be recognized if infiltration phenomena are to be properly understood. The paper shows that the initial moisture content of soil has a great influence on infiltration; that the type of soil structure, expecially in the B horizon, likewise is of great importance; and that cultivation of the soil that causes fragmentation of the B horizon is often responsible for a reduction in infiltration capacity.

Infiltration capacity is simply the capability of a mass of soil or sediment - that is, of the mantle rock of the Earth - to take liquid water into its bulk, across its boundaries, from external sources. Its measure, the infiltration rate, f, is the amount of water passing through unit boundary surface in unit time. In cgs units, for example, it is the number of cubic centimeters crossing one square centimeter of boundary surface in one second; in English units, the number of cubic feet crossing one square foot of boundary surface in one second. Numerous derived units may, of course, be set up for the convenient solution of special hydrologic problems. (The usual unit is in/hr.) In every case, however, conversion factors for transferring to the standard system of units, preferably the English, are essential so that easy conversion from one special system to another may be made, and comparison values readily obtained.

The infiltration rate f may represent only a fraction of the rate at which a soil is capable of taking up water. The capillaries of the soil are capable of transmitting much more water than is actually supplied by a given rain. The maximum rate at which a soil can transmit water at any given instant is best referred to as its infiltration coefficient (infiltration capacity) f_p. The greatest rate of infiltration, considering all times from the beginning of a rain until its end, is called the infiltration coefficient f_m, and generally occurs when the soil is very dry. The minimum rate at which a soil will transmit water occurs when the soil is saturated, and is best referred to as its minimum infiltration coefficient f_1 [HORTON 1935, COOK, 1946]. The quantities are illustrated graphically in Figure 1. These definitions will be sufficient for the present discussion.

General infiltration relations--It will be assumed in this paper that the reader is familiar with soil genesis and morphology. If not, very readable accounts exist in English [KELLOGG, 1936 and 1941; JOFFE, 1936; ROBINSON, 1932]. As a starting point it is sufficient to consider a massive soil in the morphological sense. This is simply a structureless homogeneous natural soil; for example, the weathered rock material forming the C horizon of a zonal soil. Infiltration into it is the volume of water which will cross a unit of its surface in unit time, as shown in Figure 2. Here, exists an almost ideal case, and much is to be learned by considering the passage of water through the material. For example, it will be easily recongized that the infiltration coefficient f is not in all cases a constant, independent of time and the moistrue content of the soil.

We begin with a completely dry massive soil. For convenience, consider a block of such soil isolated by a large cylinder properly jacked into the Earth. Suppose water is placed in the cylinder just over the dry soil. Liquid then enters the pores of the soil and is dragged through by grav-

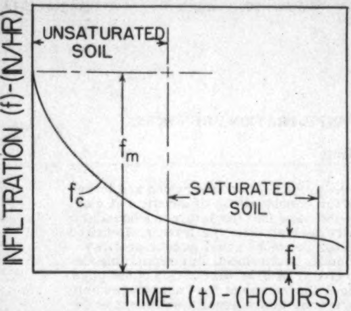

Fig. 1--Infiltration rate as a function of time in a massive soil for a rainfall of constant intensity

ity and by the capillary meniscus which forms the water front advancing into the soil. In this process air is entrapped by the capillary meniscus and remains locked in the form of bubbles, and many soil channels are thereby blocked. The transmission of water through the soil is thus decreased and, hence, the infiltration is retarded. As the meniscus advances farther, the pore length and, therefore, the hydraulic resistance increase. The infiltration rate is decreased. Eventually, the capillary meniscus reaches the bottom of the soil and passes into the underlying rock material. Gravity alone is then responsible for the conduction of water through the soil block under consideration. It is now saturated except for trapped air which, however, very slowly goes into solution. There exists a saturated flow through the soil. All swelling has taken place, conducting channels are now narrowed, with a consequent increased hydraulic resistance, and liquid flows through the soil at a uniform rate determined only by the difference in the head of liquid across the soil. Infiltration then occurs at a uniform rate; the infiltration coefficient is a minimum f_1, is constant, and is independent of time so long as the external head relations do not change. The moisture content is closely that of saturation.

It is thus apparent that the infiltration coefficient is a function of the moisture content of the soil. The rate is greatest when the moisture content is least; that is, the greater the moisture content the less the infiltration coefficient. It is least when the soil is saturated. The infiltration coefficient usually measured is that for saturated soil, and is the minimum infiltration coefficient f_1. From the foregoing, it appears necessary to distinguish between infiltration into saturated soils and infiltration into unsaturated soils.

The importance of these concepts for the estimation of runoff is easily seen. For a rainfall of constant intensity and given surface conditions the runoff - considered as rainfall less infiltration - will be a minimum where the soil-moisture content is low (customarily referred to as f_c, see Figure 1), and a maximum where the soil is saturated.

Infiltration into zonal soils--The infiltration phenomena become more complex when zonal soils are considered. For simplicity, let us consider a simple zonal soil with A, B, and C horizons, neglecting its structure for the time being. The texture and the porosity of the zones generally are very different, for each zone is separate and distinct. There are transition zones which are somewhat narrow, but these need not be considered in this discussion.

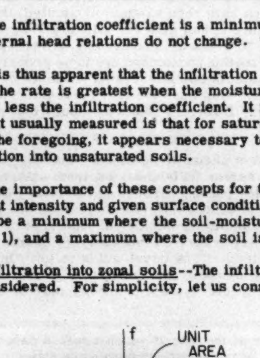

Fig. 2--Schematic representation of infiltration in a massive soil

Nonsaturated as well as saturated infiltration coefficients will be different for each horizon. Thus, the A horizon, being coarser-textured, may have a relatively great infiltration coefficient; but the B horizon with its greatly increased clay content, being finer-textured, may have an infiltration coefficient that is considerably less, and when saturated the soil may become relatively impervious. The significance of the horizón infiltration coefficient, that of the A, that of the B, and that of the C, is apparent when rainfall-runoff relations are considered. Thus, the storage capacity and the infiltration coefficient of the A horizon may be adequate to take care of a rainfall of short duration, and perhaps of high intensity; but when the rainfall is of longer duration infiltration into the B occurs and finally produces a saturated B horizon. The A horizon, in spite of a relatively high infiltration coefficient, is ineffective as a conductor of water, not because it has become saturated but rather because its ability to transmit water is limited by the B horizon's ability to imbibe it. The lower infiltration coefficient of the

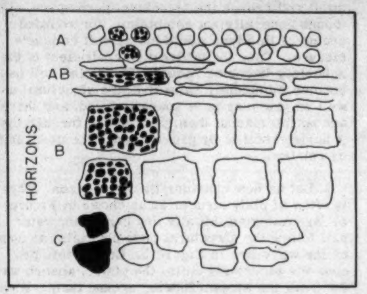

Fig. 3--Schematic representation of a structural zonal soil (gray-brown Podzol)

B horizon dominates under these conditions, and the over-all infiltration coefficient of the solum may be practically that of the B horizon. Runoff will therefore increase greatly when a heavy (in the pedological sense) B horizon dominates. The C horizon, being generally not as heavy as the B, has a higher infiltration coefficient and tends to be much less effective than the B horizon in increasing runoff.

These examples illustrate the impracticability of investigations based on composite soil samples compounded from the different horizons of the same solum. In nature, the A horizon and the upper part of the B horizon may be fragmented by plowing, but the greater part of the solum is undisturbed. Hence, aside from morphological considerations, such a sample would generally show a greater infiltration coefficeint for the solum, under some conditions, than is actually present, because of the tendency of the heavier B horizon to dominate the rate of water transfer through the solum. The actual infiltration of water into fragmented soils will be discussed after soil structure has been evaluated for its effects on infiltration, as fragmentation generally results from artificial processes applied to a structural soil.

Infiltration into structured soils--When soil structure is considered, the nonsaturation aspect of infiltration is radically altered and, to a lesser degree, that of the saturation aspect. For the purpose of this discussion, we shall adopt the nomenclature of NIKIFOROFF [1941] and consider that there are only four general classes of structure in soils - granular, blocky, platy, and prismatic. There may be, of course, as many subclasses of each of these major classes as may suit the purpose of a particular pedological investigation, but they are relatively unimportant as far as infiltration phenomena are concerned. To illustrate the phenomena, let us consider infiltration into a zonal soil of the gray-brown Podzolic great soil group. We suppose its structure to be as follows: The A horizon is granular, the AB (transition) is platy, the B is blocky, and the C is massive. Such a soil is shown in Figure 3. Let us commence with a completely dry solum. Consider the mechanism involved in the passage of water through the A horizon (see Figure 4A). Water will initially, for the most part, pass through the structural pore space as shown by the wavy lines a and b. As it passes through these larger channels some water will also enter individual granules, as shown by the lines c and d and thus enter the textural pore space proper. We have here true infiltration into morphological structure units. A capillary meniscus will form just inside the surface of the granule, as shown in Figure 4B, and advance through its pore space, that is, between the grains composing it, until the granule eventually becomes saturated.

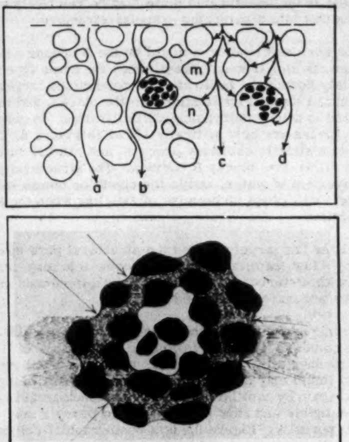

Fig. 4--Schematic representation of infiltration in the A horizon of the soil shown in Figure 2; (a) infiltration in the structural pore space of the granular A horizon; (b) infiltration in a single granule (morphological infiltration)

When the soil is unsaturated the infiltration of water through the structural pore space is chiefly by gravity, as these pores are fairly large and capillarity plays a lesser role. However, infiltration into the granules and penetration through the textural pore space of the granules is by capillarity, and morphological infiltration in soils is therefore primarily a capillary process. Let us suppose the water content of the soil to increase; then, as the granules become wetter they generally

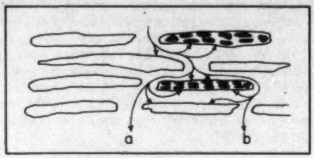

Fig. 5--Infiltration in a platy horizon

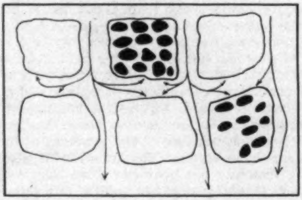

Fig. 6--Schematic representation of infiltration in the B horizon of the soil shown in Figure 2

swell and reduce the structural pore space, although generally not completely, for rounded grains of this type would not permit complete closure. Thus the infiltration coefficient of the A horizon becomes reduced. When the soil has become completely saturated, the structural as well as granular pore space is filled, and there are no interfaces; then, percolation through the A horizon soil is by gravity under the usual Darcy relation.

Let us now consider the AB horizon. This is often of platy structure, as shown in Figure 5. Assuming an initially dry condition, water will follow the structural pore channels, as shown by the wavy line in Figure 5. During this process the structural units, the plates, absorb water from the stream flowing around them. It enters the textural pore space purely by capillarity, as in the case of single granules described under granular structure.

Eventually the textural units become saturated, or nearly so, swelling has occurred, the secondary pore space is closed, and transmission of fluids is largely controlled by the textural pore space. In this connection it should be remembered that plates by their geometrical nature will permit a fairly complete closure of the structural pore space, except possibly at their edges; therefore, the permeability in the saturated state is considerably less than that of a soil possessing granular structure. For platy structure, the infiltration coefficient in the unsaturated state may be relatively high, but in the saturated state it is likely to be less than that into a saturated granular structure.

In the example chosen for this discussion the next lower horizon would be the B proper. It will be supposed to be blocky, as in Figure 6. When the soil is unsaturated, much the same type of flow takes place as occurs through granular and platy horizons. Infiltration is determined largely by the capacity of the structural pore space to transmit liquid. Infiltration into the blocks, and thus into their textural pore spaces, is by capillarity, and is a true morphological infiltration. In general, flow relations for the structural and textural pore spaces are schematically shown in Figure 6. Infiltration into a single unsaturated structural unit is a strictly capillary process, and similar to that shown in Figure 4B. Figure 7 is a photograph of a fairly dry, blocky B horizon. The structural pores present the principal channel for the downward movement of water, and in the condition shown is capable of transmitting large amounts. The channels will close up because of swelling when the soil becomes very wet, and will open again when soil dries.

When the B horizon becomes saturated, swelling has largely closed the structural pore space, transmission of water is controlled solely by Darcy's law, capillarity does not come into play, and liquid tends to move through a soil in sheet form, with disturbances caused only by differences in textural porosity. Infiltration is then determined by textural porosity and texture.

Should the B horizon be prismatic, as shown in Figure 8 (as is the case with some alkaline soils), flow relations when the soil is unsaturated are somewhat as shown in Figure 8. The flow of liquid through the secondary pore space takes place in a manner similar to that through a blocky B horizon. The structural pores are wider, however, and liquid may be transmitted through them in large quantities. Flow of water into individual prisms is again by capillarity - a true morphological infiltration. When saturation occurs capillarity is negligible and flow is according to Darcy's law, with magnitudes determined by texture and textural porosity. Figure 9A is a photograph of columnar structure in the B horizon.

C horizons are usually massive. As their flow relations have been discussed earlier, little further development is needed. They generally contain little clay, permeability is usually higher, and the infiltration capacity is somewhat greater than in the heavier B horizons.

Infiltration into fragmented soils--Fragmented soils present quite a different problem from naturally structured soils. They are generally produced from the latter by severe mechanical treatments. Plowing, together with subsequent harrowings, produces a fragmented soil to plow depth -

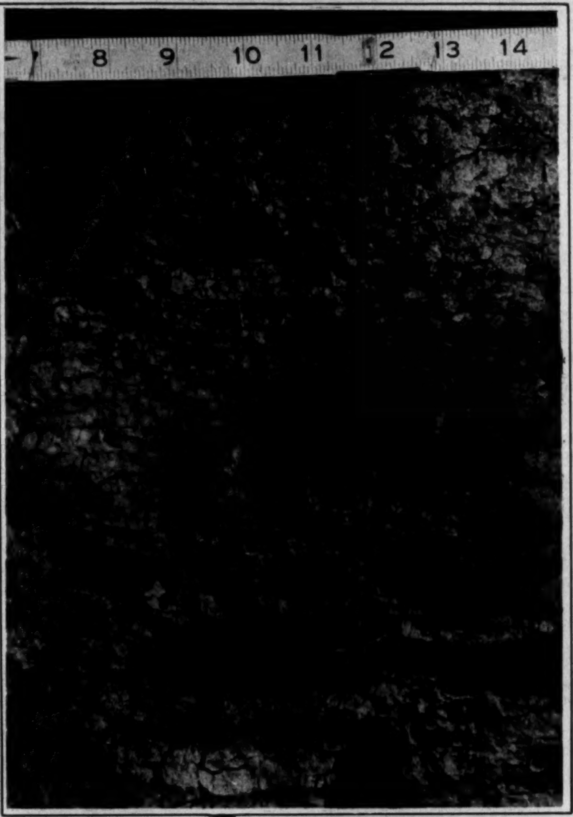

Fig. 7--B horizon of a zonal soil having blocky structure, soil fairly dry

approximately eight inches. Below this the natural soil profile is not disturbed. It should be noted, however, that continued change of the native cover under which the soils were originally developed will, in time, alter the morphology of the soils, even in the undisturbed portions. The usual laboratory treatments used to prepare soils for experimental work, that is, rolling and sieving, also produce fragmented soils.

In fragmented soils, natural structure is generally destroyed. A secondary pore space exists between the fragments, whereas single fragments possess the textural pore space and texture they possessed in the original soil, being those parts of the original structure which have survived mechanical treatment.

When water is placed on the top of a thoroughly dry fragmented soil, it infiltrates and initially enters the secondary pore space, that between the fragments. It then enters soil fragments by cap-

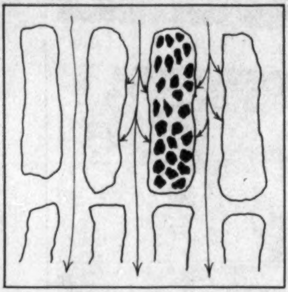

Fig. 8--Schematic representation of infiltration into prismatic structure

illarity; that is, a morphological infiltration, at least initially. However, the protective action of natural structure has been lost, as its protective coatings have been opened by the fragmentation process.

When the fragments are wetted they slake quickly, and silt and colloid go into suspension and settle to form barrier layers over the top of the soil. The extent of such action depends on the amount and kind of colloid in the soil. The permeability of layers of this kind is exceedingly low, and when these are saturated it is probably much less than that of the natural B horizon.

When a fragmented soil has become saturated, its ability to transmit water and its permeability are considerably less than that of the natural soil. Infiltration is negligible, and runoff is relatively high. Even in the unsaturated state slaking begins in single fragments that have become saturated; that is, in those fragments which have been saturated by capillary processes. The secondary pore space thus quickly closes up, expecially in the upper parts of the fragmented soil section. The upper layers become saturated and relatively impermeable. Infiltration is small, even though the middle and lower parts of the fragmented soil section may be relatively unsaturated.

It appears that fragmented soils, because of their instability in the presence of water, will generally possess infiltration coefficients much lower than the coefficients of the same soils in the nat-

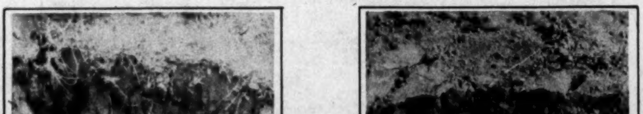

Fig. 9--Zonal soil near North Platte, Nebraska, both taken on the same day; (a) natural structure under short grass, the granular A horizon is thin; the B horizon is prismatic; the soil is dry and capable of transmitting large amounts of water to the water table; (b) a similar soil in which structure has been destroyed by plowing to depth of one foot, soil fallow and fairly moist, (as indicated by color changes) at the time the photograph was taken; it will transmit little water, but will store it ural state. Little water can reach the water table through them, although the natural soil, which has a relatively permanent structure, would be capable of transmitting large quantities to it. Much of the water falling on them leaves as runoff because of their extremely low infiltration coefficients. Figure 9 shows actual photographs illustrating these conditions; Figure 9a shows natural structure under short grass near North Platte, Nebraska. The A horizon is granular, the B horizon is prismatic. The soil is dry and capable of transmitting large amounts of water to the water table. Figure 9b shows a similar soil in which structure has been destroyed by plowing to a depth of one foot. The soil was fallow at the time the photograph was taken. It will transmit little water, but will store much. It was fairly moist when photographed, as indicated by the color changes. The infiltration capacity is low, and a heavy rain would mean large runoff.

Severe mechanical treatment, such as plowing and harrowing, conceivably may not always result in a well-fragmented soil. If the A horizon is thicker than plow depth, and granular, such treatments do little except change the packing of the granules without breaking them up. Thus, an essentially natural structure remains, which may permit even greater infiltration rates than the natural soil, provided the secondary porosity is increased. If, however, parts of the B horizon are mixed with the A during plowing, natural structural units are destroyed and the resulting slaking and sealing of the soil may occur long before complete saturation of the fragmented horizon has occurred. In all probability, colloid will enter the textural pores of the otherwise undisturbed individual granules, tending to seal them up.

Many important relationships of the problem to hydrology have not been discussed. The effect of topography, for example, has been omitted. Such questions as surface detention and temporary storage in A horizons of differing thickness have not been considered. In this connection it is well to note that depression storage will be greatly increased, in general, on agricultural lands, specifically those which have been prepared for agricultural use by mechanical treatment such as plowing and harrowing. Adjacent areas, such as virgin pasture lands not disturbed, will have very much smaller values of depression storage. Agricultural lands - that is, those specifically prepared for crops by mechanical treatments - in general will have low infiltration capacities and large runoffs, and will transmit little water to the water table. Similar soils in virgin condition will behave in reverse fashion. Fortunately, the percentage of land under cultivation is comparatively small in the United States, possibly of the order of ten per cent of the total. It is conceivable that the proportion of cultivated land might increase so substantially that the normal hydrologic pattern would be seriously disturbed.

Physical mechanisms involved in infiltration--From the foregoing it is apparent that infiltration is a function not only of porosity and texture, but also of the soil structure and moisture content. We are led at once to two important classes of infiltration: first, infiltration into unsaturated soils and, second, infiltration into saturated soils.

Infiltration into unsaturated soils is a difficult problem. Either saturated or unsaturated flow of fluids may occur in different parts of the soil. That in the structural pore space may be saturated, for example, while that in the textural pore space may be unsaturated. Thus, Darcy's law may apply to one part - for example, the structural pore space - and capillarity and other processes that move fluids in soils may predominate in other parts, such as the textural pore space.

One phase of capillarity usually may be excluded: Complete wetting generally occurs, so that contact angles are zero. The angle of wetting for water on silica and other soil minerals is zero. It is unlikely that nonwetting of organic matters, such as humus, occurs, because such organic complexes usually will be completely wetted.

When infiltration into saturated soils is considered, it is apparent that the mechanism is simpler. Capillarity is not involved except in a negligible way, and air-water interfaces do not exist in the saturated soil. Darcy's law, which governs the transmission of liquids by gravity in a system of saturated capillaries, generally regulates the flow.

In the foregoing, an attempt has been made to outline the principal features which are to be considered in infiltration problems. Both genetic and morphological relations appear to require consideration, as well as the physical mechanisms more commonly emphasized. The former constitute a boundary condition for the quantitative procedures usually derived from the latter.

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DISCUSSION

W. B. Langbein (U. S. Geological Survey, Washington, D. C.)--By and large, the subject of infiltration deserves the clarification that Smith's paper provides. There is need for an adequate explanation of the process as a framework on which to develop the many field experiments being made on infiltration. Horton, in the paper referred to by Smith, accorded infiltration a pivotal role in the relation of runoff to rainfall. As described by Smith, infiltration involves more than the passage of water through or into the surface pores of a soil. He describes the internal flow of the newly absorbed water within the upper strata of the soil.

It is particularly significant that the controls on the rate of infiltration may exist not at the surface but at a lower level, as for example the top of the B horizon. It might be suggested that other "controls" may also exist at lower horizons of discontinuity in the soil and underlying rock formations, giving rise to temporary perched water. Such perched water may in turn be the source of "wet-weather springs." To what extent each horizon of discontinuity from the surface down contributes to stream flow would depend on local conditions.

Smith gives a very plausible explanation of the effect of water on soils, and offers an explanation of their effect on runoff. Other questions to be considered from this point of view, in addition to those posed by Smith, might include (1) to what extent does the nature of the surface control the amount of precipitation that becomes runoff, and (2) what is the effect of the storage capacity of the soil below? It would seem also, that the operation of these soil factors would depend on the climate, relief, and geology, and, as far as there is opportunity for compensating effects, on areal extent.

The flow of streams is influenced by many factors; and those who keep and study records of stream flow know how unwise it may be to generalize on the effects of a single factor. Geologists are apt to generalize on stream flow on geologic principles; the climatologist feels that stream flow can be adequately explained on the basis of precipitation and temperature; the engineer and the agronomist each has his separate point of view. The writer therefore suggests that each idea has validity but only as part of a whole. To the extent that it is desired to explain stream flow, the writer would like to emphasize that postulated effects should be verified by study of stream-flow records.

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THE RELATION OF GEOLOGY TO DRY-WEATHER STREAM FLOW IN OHIO

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Abstract--The regime of dry-weather flow of several streams in Ohio is presented by flow-duration curves. For comparison, the index of ground-water flow for each basin is the discharge in cubic feet per second per square mile which is exceeded 90 per cent of the time. These indices are shown on a map of Ohio, and are discussed with respect to known geological conditions. It is concluded that stream-flow records provide useful inferences to ground-water geology, but the converse is not true.

The relation between stream flow and the climatologic factors and physical characteristics of drainage basins influencing runoff are extremely complex. The average flow of a stream over a period of many years is largely controlled by the climatologic factors but the distribution of flow throughout the year is markedly influenced by the drainage-basin characteristics, including the structure and lithology of the shallower geologic formations. The influence of these geologic factors on stream flow is perhaps most apparent during dry weather when the entire flow of the stream comes from ground-water sources.

The relation between stream flow and ground water has been studied by many different methods. The water levels in water-table wells have been successfully correlated with stream discharges [HARROLD, 1934; MERRIAM, 1942]. Normal depletion curves for streams reflect average ground-water supply. Detailed studies have been made with worthwhile results by means of a number of current-meter measurements of the inflow of short reaches of a stream (seepage runs) to determine sources and rates of ground-water flow. Several investigators in Ohio [MORSE, 1946] have compared the flow characteristics of streams, as shown by their flow-duration curves, with some of the geologic characteristics of the drainage areas. Flow duration curves for all gaging stations in the State have now been compiled, permitting a much more complete study of the relation of the geologic factors to dry-weather stream flow than has heretofore been possible.

A daily flow-duration curve is prepared by arranging all daily discharges of record in order of magnitude, and dividing them according to percentages of time specific flows are equaled or exceeded. A duration curve is asymmetrical, because there are more days of flow below the mean than above. The curve for Big Walnut Creek at Rees (see Fig. 1) plotted on Hazen's arithmetic probability paper, shows this lack of symmetry. A normal distribution plots as a straight line on this paper, and the normal distribution with the same mean and variance as the Big Walnut duration curve is plotted on Figure 1, to show the departure from normality. Hazen's logarithmic probability paper tends to result in straight or gently curving lines and is convenient in preparing curves and tables.

The shape of the lower end of the duration curve is indicative of average ground-water supply available to the stream as surface runoff. Under given climatic conditions, the regimen of ground-water flow is influenced by four geologic factors: First, the available storage space in the ground that may be filled with water in the zone of water-table fluctuation; second, the permeability of the material lying above the saturated ground-water body, or aquifer, which determines the relative amount of water that will reach the ground-water body; third, the ability to transmit water horizontally of the part of the aquifer that contributes water to the stream; and fourth, the hydraulic gradient toward the stream at different times.

Duration curves, plotted in terms of cubic feet per second per square mile for the purpose of comparison, show remarkable differences in their lower ends (see Fig. 2). These differences reflect the effects of the geology of a basin on dry-weather stream flow. For example, the curve for the Mad River is relatively high and flat at the lower end. This stream drains an area of glacial deposits consisting in large part of the gravel mounds known as kames. The thick gravel deposits serve as a huge reservoir having about the same effect as a surface reservoir or two or three billion cubic-foot capacity. Sandy Creek drains a somewhat similar area in the northeastern part of the State. Deer Creek drains an area of relatively dense and impermeable glacial till, and the curve is lower and steeper. The surficial deposits of the Portage River Basin are till and lacustrine clays, and the curve is still lower. Whiteoak Creek, in southwestern Ohio, drains an area of relatively impermeable Illinoian till, and the curve is very steep. The Little Muskingum River is in the unglac-

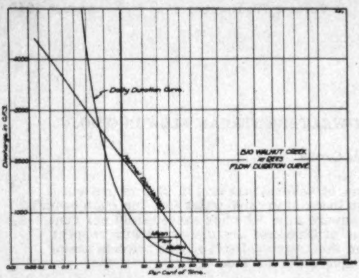

Fig. 1--Flow duration curve for Big Walnut Creek at Rees, Ohio

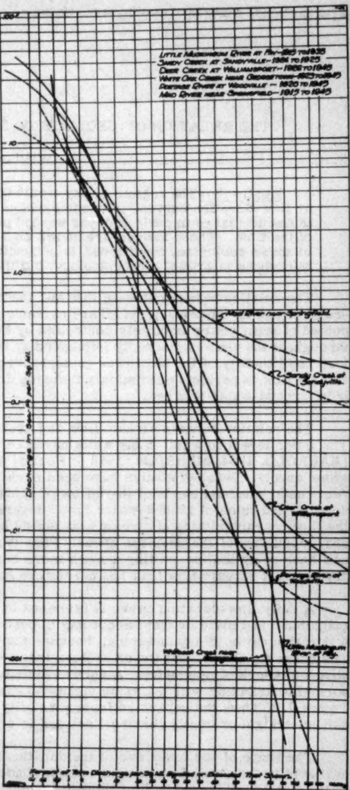

Fig. 2--Flow duration curves of selected streams in Ohio

iated part of the State, and its curve is steep but shows a higher sustained discharge than Whiteoak Creek, probably because the alluvial deposits along its course store a substantial amount of water.

The discharge which is equaled or exceeded 90 per cent of the time has been selected as an index of dry-weather flow. At this point the flow is assumed to come almost entirely from ground-water sources. Table 1 lists the average indices, based on the downstream gaging-station records, for the major drainage basins in Ohio. Figure 3 shows the outlines of the drainage areas and the indices for 141 gaging stations in the State. The records of these stations include all those available except the ones omitted because of artificial storage or diversion. The small reference numbers on the map are the same as those given by YOUNGQUIST [1947].

Table 1 of average indices shows that the basins of the Miami and Muskingum Rivers have the highest sustained ground-water flow, and the unglaciated areas and areas of dense impermeable till, the lowest. However, the data on the map show how difficult it is to generalize. It is usually possible to explain (in nearly every case) why the indices vary from area to area, but it is remarkable that, in many cases, the apparent causes for large differences in relative flow in adjacent areas are local in character, rather than area-wide. For example, the sustained flow per square mile of Big Walnut Creek at Rees is five times that of the upstream station at Central College. The difference is due to inflow of ground water to Big Walnut Creek from the thick gravels in the valley-train deposits in the "buried valley" over which the stream flows between these two gages, and not to any general area-wide factors. Whereas it is not difficult in most places to explain a high or low stream flow by the nature of the geology, it is very risky to do the opposite; that is, forecast stream flow from the geology, in the absence of discharge data.

Space does not permit a detailed discussion of all the indices. The highest sustained flows are produced in the interlobate area of the Mad River, and the lowest in areas of dense, impermeable till. The glaciofluvial deposits markedly increase dry-weather flow. The so-called buried valleys, where filled with permeable gravels and occupied by present-day streams, produce relatively high ground-water flow. Kame terraces, kames, eskers, and outwash deposits apparently have a similar effect. Some adjacent areas have widely different flow characteristics. For example, Rocky Fork

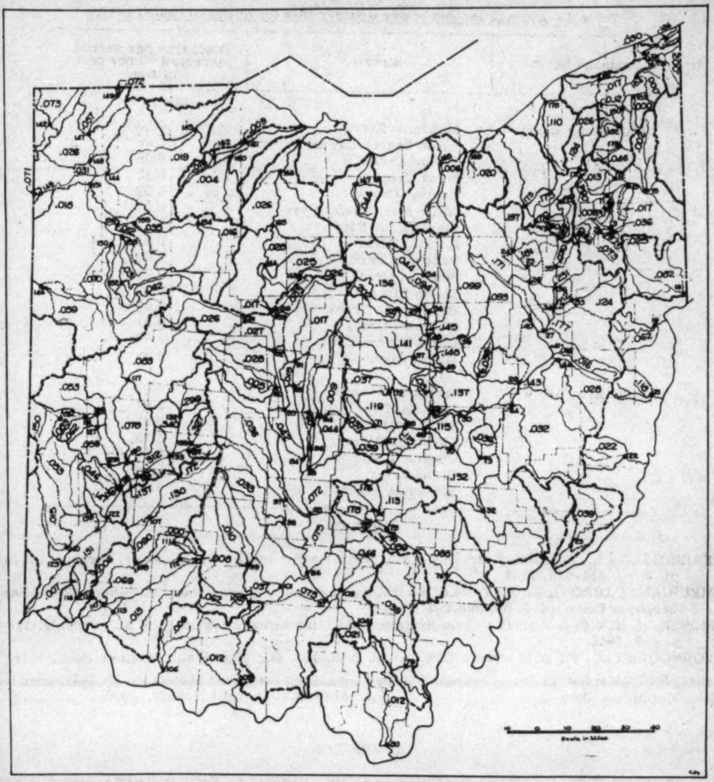

Fig. 3--Map of Ohio showing indices of dry-weather flow from duration curves

has an index six times as high as the adjacent Paint Creek drainage. The Rocky Fork basin is covered with thick sand deposits, probably outwash from the Cuba moraine, but nearby areas are mantled with relatively impermeable till.

The streams draining the unglaciated areas in the southeastern corner of the State have relatively low indices of flow. An exception is the Short Creek basin, but this anomaly is undoubtedly caused by pumpage and drainage from coal mines.

It is apparent from the foregoing that the analysis of stream-flow records may give significant evidence concerning the ground-water geology of an area, as well as indications of possible sources of ground-water supplies. However, much more would have to be known about the geologic characteristics of an area than is generally known at the present time before geologic investigations could replace stream-flow measurements as a means of predicting the amount of water available from streams. Complete answers to our water problems thus require close cooperation between geologists and engineers.

Table 1--Average indices of dry weather flow for drainage basins in Ohio

Drainage basin	Stream	Discharge per second exceeded 90 per cent of time
		cfs/sq mi
Ohio River Basin	Mahoning River	0.08
	Little Beaver Creek	0.08
	Yellow Creek	0.06
	Short Creek	0.12
	Captina Creek	0.02
	Little Muskingum River	0.04
	Muskingum River	0.13
	Hocking River	0.09
	Raccoon Creek	0.04
	Symmes Creek	0.01
	Scioto River	0.07
	Ohio Brush Creek	0.01
	Whiteoak Creek	0.01
	Little Miami River	0.07
	Miami River	0.13
Lake Erie Basin	Maumee River	0.03
	Portage River	0.01
	Sandusky River	0.03
	Cuyahoga River	0.13
	Chagrin River	0.11
	Grand River	0.02
	Ashtabula River	0.002

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U. S. Geological Survey,
Columbus, Ohio

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DISCUSSION

Walter T. Wilson (44 Loma Road, Redwood City, California)--Early in the paper there is a statement to the effect that the average flow over a period of years is controlled by climatological factors, but that the distribution of flow throughout the year is markedly influenced by the geological characteristics of the drainage basin. It might be inferred from this statement that the variation of stream flow within the year is affected so greatly by relatively unchanging geology that the annual regime changes but little from year to year. It is conceded that on the average Ohio streams experience their maximum flow in the early spring, and that the flow recedes to a minimum in the fall or winter. However, the degree to which this regime varies is indicated by the record for the Miami River at Sidney, Ohio. On pages 187 and 188 of Water Supply Paper 771 of the 8th United States Geological Survey, are sho the maximum daily discharges for each year for this stream during the period 1914 to 1934. Of the 21 years tabulated, six years had the maximum daily discharge in March. With the exception only of August and October, each month of the year is listed one or more times. This wide distribution of the time of year having the maximum discharge shows considerable variation from year to year. Study of the physical factors involved shows that both the average regime and the departures from it are highly correlated with climatological factors: rainfall and melting snow.

The foregoing is meant to be supplementary rather than critical. Cross has purposely dealt, as the title of his paper implies, with dry-weather flow. He has presented factual material in a straightforward and objective manner. The results should be useful in Ohio and vicinity, and the method could well be applied in other regions.

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FLOOD FREQUENCIES AND SEDIMENTATION FROM FOREST WATERSHEDS

Henry W. Anderson

Abstract--A multi-watershed, multi-storm, multi-variable approach was used to develop a hydrologic basis for evaluating flood control in Southern California. Flood peak discharge was shown to be related to six variables: watershed area, two storm precipitation variables, a temperature index of snow, a watershed wetness variable, and forest cover density. Since peak discharges have been measured under widely varying forest cover conditions, the partial regression coefficient for forest cover density was used to convert measured discharges to estimated discharges for a single comparable cover condition (a 40-year-old cover). Then, the estimated discharges were used in frequency analyses. The relation of discharges to storm precipitation and the wetness variables provided a means of extending the short-time discharge record to a long-time record on the basis of a 69-year record of precipitation. The relation of sedimentation of reservoirs to maximum yearly peak discharge, area of main stream channel, and forest cover density was determined. Together with the discharge frequency this provided a means of determining sedimentation frequency and mean annual sedimentation. From the determinations of the forest cover effectiveness, the effect of forest fires on peak discharges and sedimentation were evaluated for 41 watersheds.

Introduction

In the evaluation of flood prevention and control activities, information on the size and number of floods to be expected is required. Of equal importance, however, is a means for estimating the effects of flood-control measureson flood size. Past floods furnish the chief clue to future floods. If flood discharges from a watershed had been measured for several hundred years, and if watersheds had been and would remain static, then frequency of discharges could be rather easily determined. However, for most watersheds not even an approximation of such contitions exists. Watersheds have been changing and are continuing to change. Discharge records are short and have been measured under varying watershed conditions. Consequently, to evaluate flood-control measures properly it is necessary to study how changes in watersheds affect discharges, and to try to extend and adjust short-time discharge records before making estimates of future frequency.

The particular discharge event whose frequency is needed is often the peak or maximum discharge. If frequency of peak discharges can be determined, damages may be estimated. If the effect of land management or other flood-control activities on discharges can be evaluated, the reduction in damages resulting from flood-control programs may be assessed.

This paper reports a study made to obtain a hydrologic basis for evaluation of upstream flood-control programs in Southern California. It gives a method for adjusting past discharge records and for extending the period of discharge records. It also gives the relation of reservoir sedimentation to discharge and watershed characteristics. The results of the study are applied to give frequencies of discharges and sedimentation and the effect of individual forest fires and of fire-control programs on discharges and sedimentation from 41 watersheds.

Multiple regression analysis was the tool employed in the study. Correlation and regression analyses of runoff and sediment production have come into use rather recently. GOTTSCHALK [1947] has utilized the method to study the relation of sediment catches in stock ponds to the watershed variable of drainage density. Several uses of the method in connection with studies of snow-runoff relations are reported [LIGHT and KOHLER, 1943; STANLEY and KENNEDY, 1947; COOPERATIVE SNOW INVESTIGATIONS, 1947]. ANDERSON and TROBITZ [1949] used the method for a study of how some watershed variables were related to peak discharge and sediment deposition from a major flood-producing storm. The present paper is in effect an extension of the Anderson and Trobitz study, including storms of a wide range of sizes and characteristics, to permit determination of frequency of peak discharges and sedimentation from watersheds.

Physical data

The watersheds studies are on the south-facing slopes of the San Gabriel and San Bernardino Mountains of Southern California. Some of the physical characteristics of the watersheds which influence floods in the area studied are summarized here. A more detailed description is given elsewhere [ANDERSON and TROBITZ, 1949; WAR DEPARTMENT, 1946].

The watersheds studied--The watersheds are characterized by (1) steep topography, (2) highly fractured igneous and metamorphic rocks, (3) shallow, coarse-textured soils, mostly less than three feet deep, and (4) vegetation which varies from thin chamise and sage on the lower, drier sites to mixed-chaparral, oak-chaparral, and conifers on the higher and less-dry sites. Forest fires have played an important part in the watershed development. Since the advent of the white man, fires have increased, with some areas being burned and reburned, though in recent years fire protection has improved this situation. The results of past fires have been loss of soil, stream channels choked with debris, and generally drier sites. Thus, these watersheds have probably deteriorated in their capacities to resist floods since the early historical floods occurred.

Nature of precipitation--Most of the storms in the study area are associated with extra-tropical cyclones of North Pacific origin, and they often produce torrential precipitation over much of Southern California. World records of point rainfall have been recorded here: 1.02 inches falling in a one-minute period, and 11.50 inches occurring in a period of one hour and twenty minutes. Recently, 26.12 inches fell in a 24-hour period. Most of the precipitation is rain; however, some snowfall occurs in the high mountains and modifies discharges from individual storms and watersheds.

Nature and history of past floods--The mountain areas are a major source of floods. Measured peak discharges from these areas have, in recent times, been as great as 1260 cfs per sq mi for a 16.9 sq mi area, and as great as 450 cfs per sq mi for a 200 sq mi area. Discharge records before 1916 were fragmentary, but accounts of floods reach far back into early California history. Apparently most of the major floods resulted from high-intensity rainfall occurring on watersheds which had been wetted by prior rainfall. However, the flood of 1884 occurred with comparatively low intensities of rainfall [WAR DEPARTMENT, 1946], which suggests that the huge fires which occurred during the years 1878 to 1882 [BARRETT, 1935], were probably responsible for putting this flood in the major flood class. Fires probably influenced the size of other early floods also.

The flood history indicates that despite the highly fractured nature of the rocks of the watersheds, the combination of torrential precipitation and depleted watershed cover has resulted in extremely high flood incidence.

Flood damages and prevention activities--Flood damages have increased with the development of the area. In the 2,800 sq mi Los Angeles County Flood Control District physical flood damages have totaled $57,880,000 since 1884, with 90 lives reported lost [CALIFORNIA, STATE OF, 1947] In addition, a single large storm in 1938 resulted in a loss of 12 per cent of the storage space in reservoirs costing $43,000,000 [KENYON, 1939]. Total flood-control expenditures to June 30, 1946, were over $172,000,000, and additional expenditures of over $260,000,000 for dams, debris basins, channels, and other features, and over $100,000,000 for watershed improvements and retardation of silting in these structures have been proposed. Thus, within a relatively short period of time, flood control may amount to an investment of over $250 per acre or $150 per capita in Los Angeles County.

In the face of a problem of such immediate economic and social importance, watershed technicians are required to throw as much light as possible on all phases of the problem.

Data available for analysis--This study was made possible largely because of the considerable basic data that have been collected over a period of years by interested agencies. Peak discharges have been measured by the United States Geological Survey, by the Los Angeles County Flood Control District, and by the California Department of Public Works for many of the streams in the area. Sediment-deposition measurements have been made by the Los Angeles County Flood Control District and by the United States Forest Service. Precipitation measurements and compilations have been made by the United States Weather Bureau and other interested agencies. Fire histories and cover-type maps for the mountain areas have been made by the California Forest and Range Experiment Station in connection with a Fire Damage Appraisal study. Recently completed work of J. S. Horton of this Experiment Station on the relation of cover density to cover age, cover type, and geologic origin of the parent material of the soil permitted rapid approximations of the forest-cover density from other basic data. Aerial photographs and United States Geological Survey topographic maps furnish basic data on areas, physiography, vegetation, and other land features.

The time distribution of the available data of peak discharges, sediment deposition, precipitation, fire history, and flood history is shown in Figure 1. The Figure shows the period during which all the required variables were measured, which indicates the period that could be utilized in studying the relation of peak discharge and sedimentation to other variables.

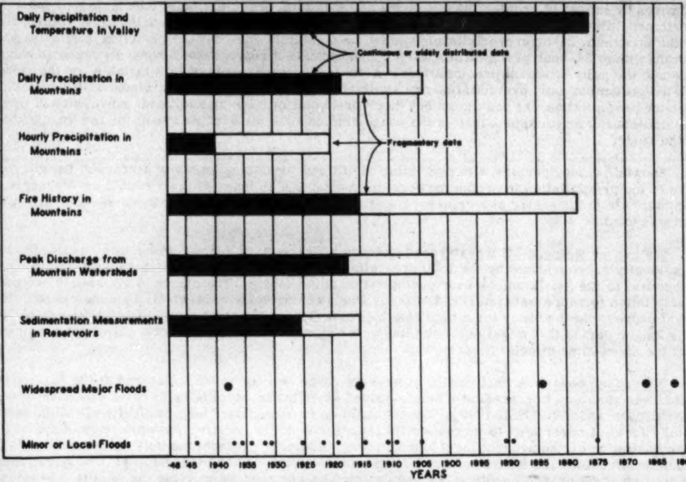

Fig. 1--Time distribution of available basic data and reported floods

Method of study

Basic premises--The following premises were made in the study: (1) That future meteorological events causing discharges will be similar to past events; (2) that the long-time meteorological record and the relation of discharges to meteorological events can serve as a basis for extending discharge records; (3) that a watershed integrates each storm and all watershed causes of floods, and that the integrated causes may be differentiated into specific variables through correlation analysis of data from many storms and many watersheds with widely varying characteristics; and (4) that valid estimates of the underlying trends of the basic variables may be thus obtained through adequate representation in both time and space and despite many side effects that may cause rather wide variations from the trends in a few events.

The statistical approach--Multiple regression analysis [EZEKIEL, 1941; FISHER, 1936], the statistical approach used permits the quantitative estimation of the separate effects of each of several independent variables on a dependent variable. (Illustrations of the use of the method may be found in papers by ZINGG, [1943], and ANDERSON, [1946 and 1947].) The method gives a measure of the significance of each of the effects, the probable range of error in the individual effects, and the error in the estimate of the independent variable made with all of the independent variables taken together. The results are expressed in the form of an equation which is compact in form and easy to use.

The statistical method required expressing each of the factors involved as variables and testing their significance in regression analyses. The choice of variables was made from those available data which on deductive ground would be expected to serve as indices of physical phenomena affecting floods and would be directly usable in evaluating flood causes.

The variables

Peak discharges may be said to vary, first, with precipitation characteristics, and second, with the watershed conditions and characteristics which influence the effectiveness of precipitation in causing discharge.

Precipitation variables influencing peak discharges--For the purpose of this study, the precipitation records were divided into storm events, a storm being defined as a period of precipitation.

unbroken by lapses of greater than 24 hours and with total precipitation of 0.02 inches or more. The storm precipitation characteristics that influence peak discharge were assumed to be representable by the maximum 24-hour precipitation and by the maximum one-hour precipitation during the storm. The maximum 24-hour precipitation was chosen because it represents in some degree both magnitude and intensity of storm precipitations. Also, long-time records of this variable, or the closely related maximum daily precipitation are available . Although closely correlated with the maximum 24-hour precipitation, the maximum one-hour precipitation gave an additional expression of intensity. The one-hour interval approximates the concentration time for surface runoff for the smaller areas in the study.

Snowfall during periods with precipitation of flood-producing intensity decreased the effectiveness of the precipitation in producing peak discharge. As an index of snow effects on discharge, the minimum air temperature at a reference station during the day of the maximum 24-hour precipitation was used.

Watershed wetness--The watershed wetness characteristic for the storm was assumed to be numerically representable by the total precipitation which had occurred during the 21-day period antecedent to the maximum 24-hour precipitation of the storm. The choice of the 21-day antecedent precipitation to represent watershed wetness was a compromise between (1) a shorter period that might express the tendency for a high residual base flow in the stream and high soil moisture, and (2) a longer period that might express total water stored in the soil and rock, but might not represent the short-time effects.

Watershed cover--An estimation of average cover density on the watershed at the time of the storm was assumed to represent a single-valued quantitative expression of cover effectiveness [ANDERSON and TROBITZ, 1949]. The assumption is reasonable, for practically all of the beneficial effects of cover tend to increase with increase in cover density: the protection of the soil from beating rain, the production of leaf litter which further protects the soil and retards surface runoff and erosion, and the secondary effects on soil structure and permeability. The cover density for the actual watershed condition for each storm was obtained by applying the density-age relations for various cover types on various geologic types as developed by J. S. Horton of the California Forest and Range Experiment Station. These relations are given elsewhere [ANDERSON and TROBITZ, 1949].

Other variables--The area of the watershed was included as a variable in order to avoid attributing effects to other variables that were correlated with areal effects. Some additional variables were tested, but proved non-significant in the form used; they will be mentioned under the analysis to which they apply.

The specific variables used in the regression analyses together with the units in which they were measured and the range of variation encountered (expressed per unit area where applicable) are given in Table 1.

Peak discharge from watersheds

The relation of the peak discharge to storm and watershed variables was determined by multiple correlation and regression analysis of 127 sets of storm-watershed data involving 29 watersheds (see Table 2) and 23 storms (see Table 3). The storms were chosen to give representative coverage of storm sizes on wet, moderately wet, and dry watersheds. The number of watershed data for a single storm varied from one to 22, depending on the storm data available. The storm and discharge data analyzed ranges in time from the May 21, 1921 storm to the February 22, 1944 storm.

Basic equations--After elimination of statistically non-significant variables, the best estimate of the relation of peak discharges to storm and watershed variables was given by the following equation.

$$\log Q = -3.245 + 1.084 \log A + 0.569 \log aP + 1.226 \log P_{24} + 0.785 \log P_1 + 3.084 \log Tm - 0.991 \log C \quad \ldots\ldots (1)$$

For definition of terms and units see Table 1. Logarithms to base 10 were used throughout. The standard error of estimate was 0.272 log units and the correlation coefficient was 0.954; the standard errors of the various partial regression coefficients were: for log A, ±0.054; for log aP, ± 0.067; for log P_{24}, ± 0.288; for log P_1, ± 0.243, for log Tm, ± 0.982; and for log C, ± 0.154. All the variables are significant at the one per cent level.

Table 1--Specific variables used in the analyses, the units employed, and ranges in the data used

Symbol	Definition	Units	Range[a]
A	Area of the watershed	sq mi	1.5-202
q	Maximum yearly peak discharge	cfs/ sq mi	10-550
Q	Momentary peak discharge from watershed during the storm	cfs	1-1260 cfs/sq mi
e_D	Sedimentation of reservoir during a single year	ac ft/sq mi	0.3-36.0
P_{24}	Maximum 24-hour precipitation for the watershed during the storm	inch	1.5-20.0
P_1	Maximum one-hour precipitation for the watershed during the storm	inch	0.2-2.1
aP	21-day precipitation antecedent to the maximum 24-hour for the storm	inch	1.0-23.0
C	Cover density on the watershed	pct	2.0-72.4
A_{Ch}	Area of main channel of the watershed	ac/sq mi	7-9.7
Tm	Minimum daily temperature at Los Angeles on day of P_{24}	^0F	45-62
ALE	Area of watershed of low elevation (below 2500 feet)	pct	0-83
Lag	U. S. E. D. half-time for runoff [WAR DEPARTMENT, 1946]	hr	0.4-3.0
$r_b r_s / r_\ell$	Watershed physiography expressed as the ratios, by stream order numbers, of stream numbers, slopes and lengths, after HORTON [1945] (r_b, r_s, and r_ℓ were expressed as ratios of larger number to smaller number.)	...	1.1-4.2

[a] Range units are the same as given for the variable unless otherwise indicated.

Eq. (1) was used in other studies to calculate peak discharges for watersheds and storms when measured discharges were missing. It is included here as the best equation for use when all the required data are available.

Although the one-hour precipitation intensity was highly significant, deficiencies in the data available obviated using this variable to extend the period of discharge records. However, the one-hour intensity was usually highly correlated with the maximum 24-hour precipitation for a storm. Similarly, inclusion of the minimum air temperature variable, to allow for snow effects, improved prediction of peak discharges for individual storms. However, snow effects tended to balance out when many events were included as in this study. Therefore, a satisfactory estimate of frequencies of discharge may be made without the one-hour intensity and the air temperature variables.

Eliminating the one-hour precipitation and minimum air temperature variables gave the following.

$$\log Q = 1.293 + 1.082 \log A + 1.870 \log P_{24} + 0.474 \log aP - 0.852 \log C \quad \ldots\ldots(2)$$

Table 2--Basic data, watershed constants for watersheds included in peak-discharge study (for explanations of variables, see Table 1)

Watershed		Variables			
No.	Name	A	ALE	$r_b r_s / r'_\ell$	Lag
		sq mi	pct		hr
1	Arroyo Seco	16.4	15	3.55	1.40
2	Big Dalton 1	4.5	40	2.91	0.69
3	Big Dalton 2	7.5	52	3.29	0.93
4	Big Santa Anita	10.8	9	2.14	0.72
5	Big Tujunga	81.4	1	2.85	2.36
6	City	19.8	16	2.37	1.39
7	Cucamonga	10.1	1	2.17	0.85
8	Day	4.8	0	2.35	0.64
9	Devil	6.2	10	3.28	0.63
10	Eaton	6.5	13	1.93	0.74
11	Haines	1.2	7	2.29	0.41
12	Little Dalton	3.3	61	2.92	0.80
13	Live Oak	2.3	83	1.10	0.65
14	Pacoima	27.8	7	3.38	2.32
15	Pickens	1.8	17	2.22	0.67
16	Plunge	16.9	10	2.54	1.29
17	San Antonio	16.9	0	2.15	0.91
18	San Dimas	15.9	26	2.65	1.21
19	San Gabriel 1	202.2	12	3.98	3.00
20	San Gabriel 2	40.4	1	4.21	1.43
21	San Gabriel 3	214.0	17	3.94	3.02
22	San Gabriel East Fork	88.5	4	4.16	2.77
23	Sawpit 1	3.3	42	1.89	0.69
24	Sawpit 2	5.3	44	2.16	0.71
25	Sierra Madre 1	1.9	0	1.85	0.45
26	Sierra Madre 2	2.4	11	2.00	0.69
27	Strawberry	8.6	14	1.95	0.88
28	Thompson	3.9	61	2.30	0.59
29	Waterman	4.6	4	2.67	0.78

Table 3--Basic data, peak discharges from some Southern California watersheds with associated storm and watershed variables (for explanations of variables, see Table 1)

Storm date	Watershed number (see Table 2)	Variables					
		Q	aP	P_{24}	P_1	T_m	C
		cfs	in	in	in	°F	pct
May 21, 1921	14	440	3.0	4.5	0.50	53	14.3
Nov. 9, 1923	6	345	1.3	2.0	0.28	58	26.4
Mar. 26, 1924	24	5	1.3	1.8	0.27	48	74.9
April 4, 1925	6	74	1.2	1.5	0.22	48	33.0
Apr. 5, 1925	24	950	1.8	2.6	0.35	45	2.0
Apr. 5, 1925	3	270	1.0	6.0	1.20	56	42.6
Apr. 7, 1926	21	14,900	1.0	8.9	1.20	56	42.0
Feb. 16, 1927	21	18,200	11.0	8.5	0.52	53	43.6
Feb. 4, 1928	6	369	1.0	3.0	0.60	48	43.0
Mar. 2, 1938	1	8,620	17.1	11.9	1.35	55	67.0
	2	1,350	10.2	8.8	1.15	55	66.1
	4	5,490	17.6	12.2	1.45	55	71.0
	5	35,000	14.2	9.1	1.20	55	67.1
	6	6,900	11.5	11.0	1.05	55	68.0
	7	10,300	13.0	15.0	2.06	55	64.1
	8	4,200	13.0	14.5	2.00	55	30.4
	9	3,320	11.5	11.0	1.05	55	69.6
	10	2,400	16.6	11.5	1.25	55	57.7
	11	265	11.9	9.2	1.20	55	58.2
	14	8,450	9.7	7.5	0.78	55	59.4
	15	1,270	11.6	9.0	1.10	55	39.6
	16	5,340	11.5	12.5	1.20	55	66.6
	17	21,400	13.0	12.5	1.90	55	50.8
	18	4,600	10.8	9.3	1.25	55	70.4
	19	90,000	17.5	11.2	1.40	55	60.4
	20	26,900	19.3	12.3	1.50	55	64.7
	23	1,000	13.9	9.4	1.05	55	60.5
	26	633	17.0	11.5	1.25	55	70.1
	27	3,360	11.5	11.0	1.05	55	60.9
	28	699	8.5	7.3	0.98	55	53.0
	29	2,350	11.5	9.0	1.00	55	67.0
Jan. 5, 1939	12	36	12.5	2.4	0.74	50	67.4
Sep. 25, 1939	4	252	1.0	7.0	1.17	62	71.2
	10	183	1.0	7.0	1.17	62	58.0
Jan. 8, 1940	1	452	2.0	3.8	0.72	56	70.0
	4	349	2.0	3.8	0.75	56	71.2
	5	2,302	2.0	4.5	0.65	56	67.1
	10	220	2.0	3.8	0.71	56	58.0
	12	63	2.0	4.7	0.56	56	68.4
	13	11	2.0	4.0	0.56	56	57.8
	14	928	2.0	4.5	0.60	56	61.0
	18	303	2.0	4.7	0.56	56	69.9

continued

Table 3--Basic data, peak discharges from some Southern California watersheds with associated storm and watershed variables (Continued)

Storm date	Watershed number (see Table 2)	Variables					
		Q	aP	P_{24}	P_1	T_m	C
		cfs	in	in	in	°F	pct
Jan. 8, 1940 (continued)	20	2,023	2.3	4.5	0.63	56	65.7
	23	39	2.0	3.8	0.75	56	62.6
	25	35	2.0	3.8	0.72	56	70.4
	28	26	2.0	4.0	0.56	56	55.0
Feb. 1, 1940	1	155	1.4	2.8	0.70	51	70.0
	4	78	1.4	2.8	0.70	51	71.6
	10	50	1.4	2.8	0.65	51	58.0
	25	8	1.4	2.8	0.65	51	70.4
Dec. 24, 1940	6	432	7.0	3.4	0.56	52	68.0
	8	137	7.0	3.0	0.50	52	40.0
	9	60	7.0	3.3	0.55	52	70.0
	27	254	7.0	3.3	0.55	52	33.1
	29	138	7.0	3.4	0.56	52	36.5
Feb. 20, 1941	1	1,340	9.0	5.2	0.96	55	70.3
	4	266	9.0	5.2	1.05	55	71.8
	7	424	6.0	4.8	0.51	55	64.2
	8	150	6.0	4.8	0.51	55	40.0
	10	317	9.0	5.0	0.97	55	58.2
	16	557	6.0	4.6	0.61	55	68.6
	20	1,637	11.0	6.5	0.80	55	66.0
	22	1,870	10.0	4.2	0.76	55	60.9
	25	55	9.0	5.0	1.07	55	70.6
	27	922	6.0	4.6	0.61	55	33.1
	29	190	6.0	4.6	0.61	55	36.5
Mar. 4, 1941	1	1,040	17.0	4.3	0.54	48	70.3
	2	88	17.0	4.3	0.54	48	72.4
	4	342	17.0	4.3	0.54	48	71.8
	5	1,568	17.0	4.0	0.49	48	67.2
	10	178	17.0	4.3	0.54	48	58.2
	12	73	17.0	4.3	0.54	48	68.4
	13	90	17.0	3.3	0.35	48	58.1
	14	815	17.0	4.0	0.49	48	61.4
	18	235	17.0	4.3	0.54	48	70.7
	25	52	17.0	4.0	0.49	48	70.6
	28	97	17.0	3.3	0.35	48	55.7
Dec. 10, 1941	6	172	2.2	3.0	0.40	50	49.0
	7	54	1.6	3.1	0.33	50	64.3
	8	20	1.6	3.1	0.33	50	45.0
	9	21	2.2	3.0	0.40	50	70.0
	16	132	2.2	3.0	0.40	50	68.6
	17	22	1.6	3.1	0.33	50	49.6
	27	102	2.2	3.0	0.40	50	38.1
	29	41	2.2	3.0	0.40	50	40.5
Dec. 29, 1941	4	42	5.0	2.6	0.49	50	71.8
	10	36	5.0	2.6	0.42	50	58.2
	11	9	7.4	2.5	0.57	50	65.0
	14	85	5.0	1.8	0.50	50	61.4
	23	5	4.0	1.6	0.50	50	63.7
	25	7	5.0	2.6	0.48	50	70.8

continued

Table 3--Basic data, peak discharges from some Southern California watersheds with associated storm and watershed variables (Concluded)

Storm date	Watershed number (see Table 2)	Variables					
		Q	aP	P_{24}	P_1	T_m	C
		cfs	in	in	in	°F	pct
Jan. 23, 1943	1	5,660	3.2	15.0	1.28	52	69.5
	2	595	3.4	12.0	1.05	52	72.3
	4	2,530	3.2	20.0	1.60	52	71.1
	5	17,850	4.0	13.0	1.20	52	67.2
	6	2,300	3.0	11.5	1.07	52	61.5
	7	1,400	3.5	13.7	1.22	52	64.3
	8	1,500	3.0	15.5	1.35	52	50.0
	9	642	3.0	13.0	1.20	52	43.3
	10	813	3.2	16.0	1.30	52	58.6
	11	142	3.0	14.5	1.50	52	67.0
	14	2,650	2.1	11.5	1.05	52	60.5
	15	185	3.2	15.0	1.50	52	56.7
	16	880	3.0	10.0	0.95	52	70.5
	17	2,100	4.0	16.5	1.48	52	50.2
	18	1,700	3.4	12.0	1.05	52	72.0
	20	15,000	4.0	20.5	1.65	52	66.0
	22	25,000	4.0	17.0	1.05	52	61.2
	23	530	3.8	18.0	1.45	52	64.7
	27	1,400	3.0	14.3	1.30	52	44.1
	29	620	3.0	14.5	1.35	52	44.6
Jan. 31, 1943	1	152	23.0	2.4	0.30	47	69.5
	4	168	23.0	2.8	0.31	47	71.1
	10	110	23.0	2.8	0.30	47	58.6
	11	20	23.0	2.1	0.30	47	67.0
Mar. 4, 1943	6	840	10.0	5.7	0.62	55	61.5
	7	319	11.0	5.5	0.45	55	64.3
	8	175	9.0	5.0	0.44	55	50.0
	16	506	10.0	5.7	0.62	55	70.5
	17	323	11.0	6.0	0.46	55	50.2
	27	371	10.0	5.7	0.62	55	44.1
	29	164	9.0	5.7	0.62	55	44.6
Feb. 22, 1944	1	1,800	8.0	7.5	1.25	46	70.0
	4	704	8.0	11.0	1.25	46	71.1
	10	390	8.0	10.0	0.94	46	58.8
	11	74	6.0	12.6	1.31	46	68.5
	25	63	7.0	7.5	0.89	46	70.9

The standard error of estimate was ± 0.301 log units, the multiple correlation coefficient was .942, and the standard errors of the various partial regression coefficients were: for A, ± 0.057; for log P_{24}, ± 0.099; for log aP, ± 0.070; and for log C, ± 0.161. All the variables were significant at the one per cent level. The regression coefficients in this equation represent estimates of the independent effects of each variable on peak discharge, when the other variables are held constant. This makes it possible to estimate the effect on discharge of changing one of the variables.

Other variables tested but found statistically non-significant were log ALE, the per cent of the watershed area less than 2500 feet in elevation; log ALE · log Tm, a joint variable of the area at low elevation with the minimum air temperature variable; log and non-log $r_b r_s / r_\ell$, a physiography variable developed by HORTON [1945] and used elsewhere [ANDERSON and TROBITZ, 1949]; a joint variable of this physiography variable with the precipitation effectiveness obtained from the three precipitation variables P_1, P_{24}, and aP; and the half-time for runoff variable lag [WAR DE-

PARTMENT, 1946]. The lack of significance in these variables must be considered merely a failure to demonstrate significance and not proof of their unimportance. As a matter of fact, with the exception of the lag variable, each variable improved the estimation of discharge somewhat (the t's in the t-test were >1.5), but the variables were not significant at the five per cent level; so it was considered that justification of their use had not been demonstrated. Other functions or joint functions may well prove them significant.

Tests were also made to check the validity of the functions used. To see whether the logarithmic cover density effect varied with size of storm, a joint variable log P_{24}/log C was tested. This variable proved to be statistically non-significant so we may conclude the log C effect is independent of storm size within the range of P_{24} in the analysis. A possible joint effect of log P_{24} and log aP was tested but also found to be statistically non-significant. Equation (2) was, therefore, considered suitable for use in determining peak-discharge frequencies and cover effects on flood frequencies.

Determining peak-discharge frequencies

A long-time record of maximum 24-hour and 21-day antecedent precipitation is basic to the application of (2) in extending the record of existing discharge data or in estimating discharge frequency for watersheds where no discharge data are available. Since no long-time record of precipitation for mountain watersheds was available, it was necessary first to extend the existing records on the basis of their relation to a 69-year record for Los Angeles or a 67-year record for San Bernardino.

The method of extension is given here for the single watershed, Big Santa Anita, which had a precipitation station at Mt. Wilson, at the head of the watershed, for 30 years. The average precipitation for the watershed has been estimated by P. B. Rowe to be that at Mt. Wilson times a factor of 0.98. The 30-year record of precipitation was extended to a 69-year record through the use of free-hand-fitted curves, expressing (1) the relation of maximum daily precipitation at Big Santa Anita to that at Los Angeles for individual storms of different storm sizes (30-year record); (2) the relation of the 21-day antecedent precipitation for the two areas; (3) the relation of number of storms in different storm sizes for the two areas; and (4) the relation of maximum daily to maximum 24-hour precipitation for different sizes at Big Santa Anita. After the curve was obtained for any of these variables, appropriate values were inserted for precipitation at Los Angeles; and thence were obtained estimates of precipitation for Big Santa Anita watershed (Table 4). For individual events such a method of extension of records from a valley point to a mountain watershed may be in error, but the correlation is high and on a frequency basis deviations would be expected to offset each other.

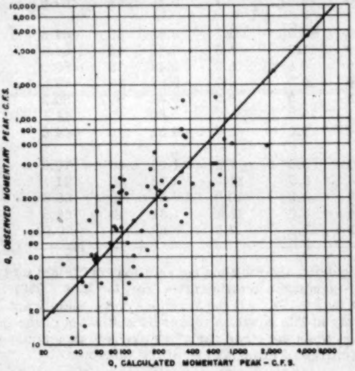

Fig. 2--Relation of the observed peak discharges for Big Santa Anita watershed to the computed discharges for the same storms, calculated from Eq. (2)

Having an extended precipitation record, the frequency of peak discharges was obtained in four steps, as follows.

(1) Eq. (2) was used to calculate the peak discharges for all of the storms of the long-time precipitation record given in Table 4. (The actual storm sizes were used for the large events and the means of the groups of Table 4 for the small events.)

(2) Observed discharges for Big Santa Anita were adjusted to a comparable cover conditions a 40-year-old cover by a method to be described later. (For most cover types the cover density-cover age relations are accretion curves in which cover density reaches a maximum in from 25 to 40 years, and thereafter remain essentially constant, hence the choice of 40-year-old cover for comparisons.) As Big Santa Anita had not been burned since 1910, the necessary adjustments in this case were minor.

(3) For all storms occurring during the period of discharge record (October 1, 1916, to April 30, 1946) the calculated discharge was plotted against the observed discharge for the storm (see Fig. 2).

(4) On the basis of the trend line of Figure 2, the calculated discharges for the period of no observed discharges (October 29, 1877 to September 30, 1916) were corrected.

Table 4--Maximum daily precipitation of storms and associated 21-day antecedent precipitation for Big Santa Anita watershed

Maximum daily precipitation	Number of storms with 21-day antecedent precipitation (in inches) of											
	<2.00		2.00-3.99		4.00-7.99		8.00-15.99		16.00-31.99		>31.99	
in	a	b	a	b	a	b	a	b	a	b	a	b
0.02-0.99	765	325	147	68	120	50	74	24	32	12	1	1
1.00-1.99	130	51	45	26	35	17	31	13	6	2	0	0
2.00-2.99	38	16	21	10	25	17	14	4	8	5	0	0
3.00-3.99	22	8	7	3	9	5	11	3	2	1	0	0
4.00-4.99	7	5	9	3	9	3	5	4	3	2	1	0
5.00-5.99	0	0	3	1	3	2	3	2	2	0	0	0
6.00-6.99	2	1	2	0	3	1	1	1	0	0	0	0
7.00-7.99	1	0	0	0	0	0	1	1	0	0	0	0
8.00-8.99	3	1	1	0	0	0	0	0	0	0	0	0
9.00-9.99	0	0	0	0	0	0	1	1	0	0	0	0
10.00-10.99	3	0	0	0	0	0	1	0	0	0	0	0
11.00-11.99	1	1	0	0	0	0	0	0	1	1	0	0
12.00-12.99	0	0	0	0	0	0	0	0	0	0	0	0
13.00-13.99	0	0	0	0	1	0	0	0	0	0	0	0
14.00-14.99	0	0	0	0	0	0	0	0	0	0	0	0
15.00-15.99	1	1	0	0	0	0	0	0	0	0	0	0
Totals	973	409	235	111	205	95	142	53	54	23	2	1
Grand total of all storms					1,611	692						

[a] For the period Oct. 29, 1877 to Apr. 30, 1946.
[b] For the period October 1, 1916 to April 30, 1946.

The 30 years of observed peak discharges plus the 39 years of corrected calculated peak discharges constituted an estimate of discharges for the 69-year period for 40-year-old cover from which the frequency was obtained.

From the standpoint of discharge frequency, the relation established in Figure 2 constituted a correction of the calculated discharges for nearly all the individual characteristics of the watershed that affected the discharges. That is, the discharges are corrected for the effects of the geology, shape, and other physiographic features of the watershed, for errors in measuring watershed precipitation, and for snow effects. Although there is considerable dispersion about the trend line of Figure 2, still the estimate of the frequency for this short period is good. One method of showing this is by comparing the frequency of the observed discharges and the frequency of the corrected calculated discharges for the same period (see Fig. 3). The comparison is favorable; so the extended 69-year record of peak discharges, both maximum yearly and all events, for Big Santa Anita were arranged and plotted by the method of HAZEN [1930] to give the frequency curves (Fig. 4). The discharge points may be used in other plotting formulas if desired.

To determine the long-time frequency of peak discharges for other watersheds that had some peak-discharge records the method could have been repeated. However, if the watershed experienced

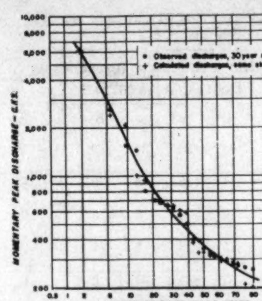

Fig. 3--Test of relation of observed to calculated peak discharges for Big Santa Anita watershed by comparison of frequency points

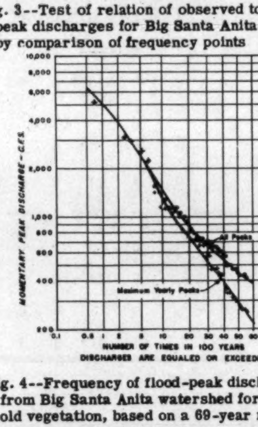

Fig. 4--Frequency of flood-peak discharges from Big Santa Anita watershed for 40-year-old vegetation, based on a 69-year record

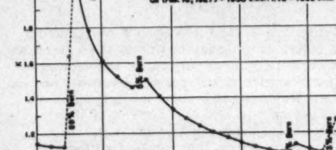

Fig. 5--Illustration of the adjustments of observed discharges to their estimated size under a constant cover condition (a 40-year-old cover) by using Eq. (2); City Creek watershed, 19.7 sq mi

in general the same storms as Big Santa Anita the method could be greatly shortened by taking advantage of correlation between discharges of watersheds. First, however, all the peak discharges of the new watershed were brought to a common basis of cover density (40-year-old cover) by making the adjustment mentioned previously as Step (2).

The average cover density of the watershed at the time of each peak discharge was determined by weighting areas of cover density obtained by applying cover ages, cover types, and geology to curves drawn from the equations given elsewhere [ANDERSON and TROBITZ, 1949]. The correction of the peak discharges was on the basis of the relationship between cover density and peak discharge which is a part of (2). The correction of the discharges from City Creek watershed may serve as an illustration. Figure 5 shows the factor K by which the observed storm-peak discharges in each water year must be divided to convert them to their estimated size under a 40-year-old watershed-cover condition. The magnitude of this correction factor varies with time as shown, being greatest in 1923, after the 1922 burn which denuded 59 per cent of the watershed, and being least in 1938, after 16 years of vegetation recovery with only a single five per cent burn in the interval.

The determination of the correction factor K for the single year 1927 is illustrated in Figure 5, where K = antilog $[0.852 \log(C_R/C_P)]$, C_R is the 40-year-old cover density (75.0), and C_P is the cover density present on the watershed in 1927 (48.4). The correction of the discharge for a single storm, that of February 16, 1927, is also shown. Thus, the adjusted 1330 cfs discharge was used for that storm in the frequency analysis instead of the observed 1930 cfs. Similar adjustment curves were drawn for all watersheds, and all discharges were adjusted before being used. The magnitude of these adjustments varied widely between watersheds: The maximum reduction applied to observed discharges was as little as four per cent (K = 1.04) for Big Santa Anita, and as great as 89 per cent (K = 8.8) for Fish Canyon the first year after a nearly complete burn. By use of these adjustments, the discharge records for each watershed were transformed to a single comparable watershed condition.

The method of obtaining peak-discharge frequency for a watershed by extending the record on the basis of the correlation of its discharge with those of a watershed whose long-time frequency has been determined can be illustrated for San Gabriel watershed 2, area 40.4 sq mi. The observed peak-discharge measurements at the gaging station for the 15-year period were each adjusted to what they would have been had the watershed has a constant cover density of 69.1 per cent, that is, a 40-year-old cover age. The adjusted 15-year record of discharges was extended to a 69-year record by the relationship

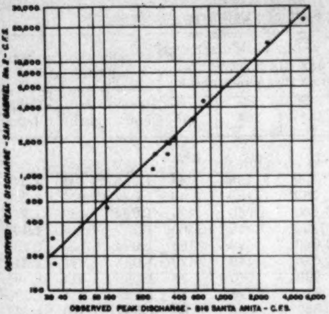

Fig. 6--Relation of peak discharges of San Gabriel watershed 2 to those of Big Santa Anita watershed for the same storms after correcting discharges to a common basis of 40-year-old vegetation

of these discharges to those of Big Santa Anita for the same storms (see Fig. 6). The 69-year record was used to plot frequency of maximum yearly discharges for 40-year-old cover as was done for Big Santa Anita.

Forest fire effects on peak discharges

To estimate the effect of fire protection programs or of individual forest fires on discharges, the cover-discharge relationships of (2) may again be used. The method may be illustrated for San Gabriel watershed 2: From the fire history by cover types of the areas in and adjacent to San Gabriel watershed, the expected annual burn with the present fire protection level was found to be 0.77 per cent of the watershed area. Thus on the average, there would be a cover density of 66.2 per cent on the watershed. From the cover-discharge relationship, the effect of the present burn on flood frequency is to multiply the discharges for 40-year-old cover (cover density 69.1 per cent) by a factor of 1.037 (from antilog 0.852[log (69.1/66.2)]). For a fire-protection program which would reduce the average annual burn to 0.20 per cent of the watershed (cover density 68.4 per cent), the peak-discharge frequency was obtained by multiplying the discharges for the 40-year-old cover by a factor of 1.007. The effect on peak discharges of a large burn in 40-year-old cover, say a 7.4 sq mi fire equal to one-fourth of the brush zone, is to multiply the size of the peak discharge the first year after the fire by 1.187.

Using the same methods, frequencies of peak discharges were obtained for all sub-watersheds of the San Gabriel, Santa Ana, Santa Clara, and Ventura Rivers. The discharges for all watersheds are summarized in Table 5 in such a manner that the frequency curves for various watershed burn conditions may be duplicated.

Sediment deposition from watersheds

An estimation of sediment deposition from watersheds was based on the frequency of peak discharges from the watershed and the relation of actual measured sedimentation to peak-discharge and watershed variables. Since very few single storm catches of sediment have been measured, it was decided to test the relation between the yearly catches of sediment and the maximum yearly peak discharge, with other watershed variables included in the analysis. The maximum yearly discharge, then was used as an index of the yearly sediment-producing potential. Other variables included in the analysis were cover density and area of main stream channel. It was recognized that additional variables probably influence sediment production from watersheds, but sedimentation data now available did not seem to justify a more detailed analysis using this sedimentation-discharge relation.

Basic equation--Multiple regression analyses were made of 23 yearly catches of sediment in reservoirs (see Table 6), from watersheds that varied in area from 4.5 to 202 sq mi. Eq. (3) gave the best estimate. (For definition of terms and units see Table 1.)

$$\log e_D = 1.041 + 0.866 \log q + 0.370 \log A_{Ch} - 1.236 \log C \ldots\ldots\ldots\ldots (3)$$

The standard error of estimate was ± 0.184 log units and the multiple correlation coefficient was 0.953. The standard errors of the regression coefficients were: for log q, ± 0.068; for log A_{Ch}, ± 0.250; and for log C, ± 0.956. The variable peak discharge is significant at the one per cent level. The other two variables, area of channel and cover density, have been included here because each is significant at the five per cent level when tested separately in an equation with peak discharge; so rather than using one or the other, both are included to give the most reliable measure of their individual effects and the best estimate of sedimentation.

Determining average annual sedimentation of reservoirs--Substituting in (3) the appropriate constants for cover and channel area, together with the maximum yearly peak discharges (see Table 5) obtained from the frequency analysis, gives the frequency of yearly sedimentation and a calculated average annual sedimentation.

Table 5--Estimated peak discharges from Southern California watersheds

Sub-watershed names	Area	Area of brush	Present average annual burn	Maximum yearly peak discharge for 40-year-old forest cover for selected frequency points				Factors to convert discharges[b]		
				1[a]	5[a]	20[a]	50[a]	Present[c]	Program[d]	Large burn[e]
	sq mi	sq mi	pct	cfs	cfs	cfs	cfs			
Big Dalton	4.5	4.4	0.9	1,070	490	168	44	1.088	1.012	1.272
Big Dalton	2.7	2.7	0.9	660	330	150	46	1.087	1.012	1.269
City	19.7	19.7	1.5	5,600	3,600	1,050	290	1.094	1.010	1.275
Coyote Creek	41.0	31.5	2.0	16,000	8,200	3,200	1,500	1.137	1.010	1.198
Cucamonga	10.1	9.2	1.5	9,200	2,600	790	185	1.074	1.009	1.250
Day	4.8	3.7	1.5	2,800	1,030	230	120	1.081	1.011	1.212
Deer	3.7	2.6	1.5	3,000	910	270	90	1.089	1.011	1.195
Devil	6.2	6.1	1.5	2,600	580	125	57	1.089	1.014	1.270
East Etiwanda	3.1	3.1	1.5	1,210	530	120	60	1.082	1.010	1.275
Fish	6.5	6.5	0.9	2,500	1,500	490	220	1.083	1.012	1.278
Little Dalton	3.3	3.3	0.9	730	330	150	74	1.105	1.013	1.278
Little Sand	1.5	1.5	1.5	400	140	35	14	1.157	1.017	1.275
Live Oak	2.3	2.0	0.9	290	160	83	42	1.137	1.016	1.234
Lone Pine	15.3	14.5	1.5	5,000	1,400	730	130	1.100	1.014	1.261
Lytle	47.9	22.0	1.5	20,000	6,700	1,530	430	1.061	1.010	1.127
Matilija Creek	55.0	46.4	2.0	14,000	8,000	3,400	1,700	1.150	1.014	1.222
Mill	43.2	23.7	1.5	16,100	3,000	870	350	1.052	1.007	1.153
Piru Creek	432.0	226.0	1.4	32,000	17,000	6,500	2,900	1.079	1.010	1.127
Potrero	31.0	18.9	3.2	13,000	4,800	1,480	6,900	1.272	1.072	1.167
Plunge	16.9	16.9	1.5	4,350	1,900	740	310	1.095	1.010	1.275
Roberts	6.4	6.2	0.9	2,300	1,200	470	160	1.084	1.012	1.278
San Antonio	26.7	14.9	1.5	12,100	3,300	620	160	1.056	1.007	1.157
San Dimas	15.9	15.9	0.9	4,200	1,700	680	240	1.079	1.012	1.277
San Gabriel 1	202.0	135.3	0.6	79,000	37,000	13,000	4,000	1.056	1.026	1.168
San Gabriel 2	40.4	29.5	0.8	24,000	12,000	4,000	1,500	1.037	1.007	1.187
San Jacinto	140.0	81.2	1.5	53,000	14,500	2,600	860	1.122	1.015	1.160
San Jose	80.2	25.4	0.7	12,300	7,700	4,200	1,900	1.053	1.005	1.072
Santa Ana	144.0	72.0	1.5	53,000	14,000	4,000	1,900	1.045	1.008	1.148
Santa Ana near Prado	1,465.0	875.0	2.1	90,000	12,600	4,600	2,400	1.080	1.010	1.165
Santa Clara River	355.0	259.0	1.4	36,000	16,000	4,700	1,640	1.105	1.014	1.186
Santa Paula Creek	40.0	31.6	2.0	13,400	7,400	3,000	1,500	1.134	1.012	1.207
Santiago	63.0	47.5	1.5	11,600	5,200	1,600	470	1.112	1.013	1.207
San Timoteo	118.0	63.1	2.4	6,800	3,300	1,340	470	1.125	1.025	1.148
San Sevaine	1.9	1.0	1.5	720	307	100	37	1.088	1.010	1.147
Sespe Creek	254.0	208.0	2.0	61,000	32,000	12,000	5,500	1.177	1.014	1.218
Strawberry	8.6	8.4	1.5	3,050	1,000	280	110	1.062	1.008	1.270
Temescal	135.0	93.8	2.4	13,400	4,600	1,200	250	1.112	1.013	1.192
Upper Cajon	40.9	39.3	1.5	14,100	8,500	2,250	640	1.118	1.016	1.264
Ventura River	187.0	133.7	2.0	43,000	24,500	11,000	5,600	1.137	1.012	1.183
Waterman	4.6	4.5	1.5	1,950	770	270	112	1.076	1.008	1.267

[a] Estimated number of times in 100 years peak discharges listed are equalled or exceeded.

[b] Discharges for 40-year-old cover times factor converts discharges to other conditions.

[c] Factor for present watershed cover condition with present fire-protection level and estimated average annual burn.

[d] Factor for watershed cover conditions expected under the proposed improved fire-protection program--0.2 per cent average annual burn for all watersheds except Santa Ana at Prado, San Timoteo, and Temescal where the proposed is 0.5 per cent and Potrero where it is 1.0 per cent.

[e] Factor for first year after a large burn (in 40-year-old cover) that equals one-fourth of the brush area in the watershed. Larger burns are probable in small watersheds.

Table 6--Basic data of yearly reservoir sedimentation and associated maximum yearly discharge, area of main stream channel, and forest-cover density for some Southern California watersheds

Watershed	Water year	Sedimentation	Maximum yearly discharge	Area of channel	Forest-cover density
		ac ft/sq mi	cfs/sq mi	ac/sq mi	pct
Pacoima	1937-1938	18.0	300	9.7	59.4
Santa Anita	1942-1943	12.2	290	1.7	71.1
San Gabriel 2	1937-1938	36.0	610	5.0	64.7
San Gabriel 1	1937-1938	32.3	550	6.8	59.1
San Gabriel 1	1940-1941	5.1	36	6.8	60.5
San Gabriel 1	1942-1943	10.7	286	6.8	61.0
San Gabriel 1	1943-1944	2.9	30	6.8	61.5
Arroyo Seco	1934-1935	4.3	43	7.3	57.0
Arroyo Seco	1935-1936	5.6	43	7.3	60.0
Arroyo Seco	1942-1943	14.3	252	7.3	69.5
Big Dalton	1934-1935	1.3	11	3.4	45.9
Big Dalton	1935-1936	0.6	16	3.4	64.8
Big Dalton	1936-1937	1.6	22	3.4	65.4
Big Dalton	1937-1938	14.9	294	3.4	66.1
Big Dalton	1940-1941	0.8	20	3.4	69.2
Big Dalton	1942-1943	5.8	132	3.4	72.3
San Dimas	1935-1936	0.3	10	4.1	67.0
San Dimas	1936-1937	1.4	18	4.1	70.0
San Dimas	1937-1938	13.3	310	4.1	70.4
San Dimas	1940-1941	2.8	15	4.1	70.7
San Dimas	1942-1943	4.7	107	4.1	72.0
Big Tujunga	1937-1938	18.5	405	4.6	67.1
Big Tujunga	1943-1944	2.1	34	4.6	67.2
Totals		209.5	3,834	115.6	1,491.9

Whenever possible calculated sedimentation for individual watersheds was tested by comparison with actual measured sedimentation. It was inferred that differences between totals of actual sediment catches and sedimentation estimated from (3) for the same period may well have been due to differences in that watershed not evaluated by variables in the equation. Adjustment to allow for those differences was therefore made. This may be illustrated for San Gabriel watershed 1. The total measured sedimentation during the seven-year period of 1937-1938 to 1943-1944 from the 202 sq mi watershed was 59.2 ac ft per sq mi. The sedimentation calculated from the seven maximum yearly discharges and the watershed conditions during the same period was 51.5 ac ft per sq mi. The ratio of actual to calculated sedimentation was therefore 1.15. The calculated average annual sedimentation (for 40-year-old cover), obtained from application of the peak discharge frequency, was multiplied by this factor, giving the corrected estimate of average annual sedimentation for that watershed.

In estimating the effect on sedimentation of single forest fires or management programs which affect cover density, a dual effect of cover must be taken into account: Cover changes affect discharges according to the relationship in (2), and cover changes have an additional effect on the amount of sedimentation for a given discharge according to the relation of (3). Working the cover change first through the discharge equation and then through the sedimentation equation gave the effect of changing cover on sedimentation. The same effect is obtained by substituting the cover change in an equation obtained by combining the discharge and sedimentation equations.

$$\log e_D = 2.161 + 0.071 \log A + 1.619 \log P_{24} + 0.410 \log aP + 0.370 \log A_{Ch} - 1.974 \log C \quad . . (4)$$

P_{24} and aP in this equation are for the maximum storm of the year.

The sedimentation results by watersheds are summarized in Table 7; included are estimates of sedimentation under various fire-protection levels and also the effect of a large watershed burn on the sedimentation from a storm of 0.01 frequency.

Table 7--Estimated sedimentation from Southern California watersheds

Watershed	Area	Area of brush	Present average annual burn	Average annual sedimentation		Sedimentation from 0.01 frequency flood[c]	
				Present[a]	Fire Program[b]	Fire Program[b]	Large burn[d]
	sq mi	sq mi	pct	c y/sq mi	c y/sq mi	c y/sq mi	c y/sq mi
Big Dalton	4.5	4.4	0.9	2,710	2,435	19,000	33,000
Big Dalton	2.7	2.7	0.9	2,930	2,620	16,200	28,000
City	19.7	19.7	1.5	3,230	2,660	19,100	33,400
Coyote	41.0	31.5	2.0	3,670	2,800	16,100	24,400
Cucamonga	10.1	9.2	1.5	8,630	7,460	60,000	99,300
Day	4.8	3.7	1.5	9,770	8,280	50,300	77,200
Deer	3.7	2.6	1.5	7,340	6,120	76,300	113,000
Devil	6.2	6.1	1.5	3,180	2,670	40,700	70,400
East Etiwanda	3.1	3.1	1.5	4,590	3,870	34,000	59,000
Fish	6.5	6.5	0.9	4,040	3,630	17,500	30,900
Little Dalton	3.3	3.3	0.9	3,150	2,830	17,600	31,000
Little Sand	1.5	1.5	1.5	3,800	2,700	26,300	46,000
Live Oak	2.3	2.0	0.9	2,650	2,270	10,700	17,500
Lone Pine	15.3	14.5	1.5	3,200	2,640	35,800	62,000
Lytle	47.9	22.0	1.5	6,560	5,850	68,500	90,000
Matilija	55.0	46.4	2.0	4,150	3,100	14,600	23,600
Mill	43.2	23.7	1.5	8,550	7,660	53,100	72,500
Piru	432.0	226.0	1.4	2,600	2,230	12,500	16,500
Potrero	31.0	18.9	3.2	7,430	5,000	33,200	46,500
Plunge	16.9	16.9	1.5	3,330	2,770	23,600	41,400
Roberts	6.4	6.2	0.9	3,440	3,080	15,700	27,700
San Antonio	26.7	14.9	1.5	6,280	5,650	73,000	100,000
San Dimas	15.9	15.9	0.9	3,400	3,080	23,400	41,100
San Gabriel	161.6	105.8	0.6	7,080	6,780	50,000	71,000
San Gabriel 2	40.4	29.5	0.8	5,050	4,440	28,800	42,800
San Gabriel 1	202.0	135.3	0.6	6,675	6,310	45,600	65,100
San Jacinto	140.0	81.2	1.5	4,150	3,290	40,400	55,700
San Jose	80.2	25.4	0.7	2,115	2,030	8,400	9,900
Santa Ana	144.0	72.0	1.5	3,220	2,950	37,000	50,000
Santa Ana near Prado[e]	1,465.0	875.0	2.1	600	516	8,350	11,600
Santa Clara	355.0	259.0	1.4	2,730	2,240	18,200	27,000
Santa Paula	40.0	31.6	2.0	2,990	2,300	11,800	18,100
Santiago	63.0	47.5	1.5	3,230	2,600	21,400	32,400
San Timoteo	118.0	63.1	2.4	1,570	1,265	8,450	11,400
San Sevaine	1.9	1.0	1.5	4,620	3,850	40,000	54,000
Sespe	254.0	208.0	2.0	3,850	2,680	15,700	24,400
Strawberry	8.6	8.4	1.5	2,950	2,600	34,700	60,000
Temescal	135.0	93.8	2.4	1,360	1,090	10,500	16,500
Upper Cajon	40.9	39.3	1.5	6,580	5,260	41,000	70,000
Ventura	187.0	133.7	2.0	4,590	3,500	16,300	24,100
Waterman	4.6	4.5	1.5	4,840	4,070	39,500	68,000

[a] Present condition of watersheds and present burn per cent.

[b] Expected after proposed fire program is effective--that is, if average annual burn is reduced to 0.2 per cent for all watersheds except Santa Ana above Prado, San Timoteo, and Temescal where the proposed is 0.5 per cent and Potrero where it is 1.0 per cent.

[c] Sedimentation expected from flood which frequency study shows will be equalled or exceeded once per hundred years.

[d] First year after large burn which equalled 1/4 of the brush area in watershed.

[e] An estimated 15 per cent of above deposition will pass through Prado.

This study indicated that measured average annual sedimentation of individual reservoirs is often not a good index of the long-time average to be expected. If the record of sedimentation was short, the floods during the period may not have been representative. Even if the record of sedimentation was fairly long, the fire history may not have been representative or the coincidence of fires and storms may have been exceptional.

Conclusions

The method employed complies fairly well with six criteria which the adequacy of a study in applied hydrology may be evaluated. In determining the basic relations (1) the data are representative in time; this was considered to be fairly well met because the data used covered more than a 20-year period, (2) the data used are representative in space; the watersheds included extended along a 100-mile mountain front, (3) the effects measured are representative of actual effects; in this case they were the actual effects of meteorological and watershed variables on discharges from whole watersheds and sedimentation of actual reservoirs, (4) the effects measured are related to the desired and products; the damages produced by floods, (5) a suitable measuring device was employed; multiple regression analysis, and, in the application of the results, (6) tests were made for the individual cases whenever possible and adjustments made on the basis of those tests.

Other uses of the equations than those made here suggest themselves. The precipitation effectiveness obtained from the equations may serve as a tool for studying deterioration of watersheds with repeated burnings and subsequent storms. In addition, now it may be possible to use precipitation effectiveness and the voluminous data on sedimentation for which no associated discharges were available in a better study of the influence of watershed variables on sedimentation.

Acknowledgments

The approach used in this study has properly been called "organized experience, statistically evaluated." Besides the contributions in the literature to this organized experience, the author desires to acknowledge the essential contributions made by his fellow workers. He is indebted to D. M. Ilch and others of the Forest Service Flood Control Survey group who knew what was needed and gave suggestions as to how it might be obtained; to H. K. Trobitz for his active help and many suggestions; to P. B. Rowe and J. S. Horton of the California Forest and Range Experiment Station for furnishing much of the data, making suggestions, and providing the results of their own research prior to publication; and to Joseph Kittredge of the University of California, H. G. Wilm of the Southern Forest Experiment Station, and P. B. Rowe for reading the paper critically.

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DISCUSSION

Leonard Schiff (Soil Conservation Service, Coshocton, Ohio)--The author is to be commended for the manner in which he has treated a large number of variables of possible physical importance in the problem involving the influence of land management on peak discharges. This paper deals with watersheds ranging in size from less than 1.0 to 202 sq mi. It would seem that the 21-day watershed wetness variable, selected as a compromise, and the elimination of the one-hour maximum precipitation variable because of lack of data, would particularly distort the relationships between peak discharges and the variables for small watersheds. Using the shorter equation and relating calculated momentary peaks to observed momentary peaks, the scatter of points for the large watersheds as well as the small watershed is fairly wide. Perhaps better results could be obtained if watersheds were grouped in area ranges and equations developed for each. Results might also be improved if the watershed wetness variable could be expressed in terms of soil moisture. If information on soil moisture is not availalbe, it might be estimated from the precipitation for a given period of time and soil-moisture depletion for this same period.

For the Big Santa Anita Watershed of 10.8 sq mi for an observed peak of about 250 cfs, approximately 12 calculated peaks scattered from about 80 to 1,000 cfs. The trend line, established through the scattered points for the 30-year record of Big Santa Anita Watershed, was used to correct the calculated discharges for the 39-year period of no observed discharges. The method of correction was not described but it may be the main reason for the close agreement between the frequency curves based on the calculated peaks and the observed peaks. Obviously, the ability to establish correctly the position of the trend line through the widely scattered points is important. The author's general approach is appreciated, first, in extending a short record on some rational basis as there may be doubt as to how representative a shorter series may be, second, all peaks as well as maximum yearly peaks were used in developing frequency curves which indicate how often a given peak is equalled or exceeded in the period considered, and third, the frequency curves are curved to fit the points as closely as possible.

Cover may actually be more significant than found for estimates of sedimentation, but the type of test made was limited by the data. It should be borne in mind that sediment removal results from a process of detachment and transportation over a period of time involving sequences of storms. Cover resists detachment of soil perhaps more than it reduces peak discharges at a given point. However, cover may considerably change the make-up of peak discharges from surface to subsurface contributions. Such changes could reduce sediment removal without appreciably reducing peaks.

To focus his problem the author gave major consideration to the influence of cover on peak discharges. His equations show cover to be highly significant in its reduction of peak discharges, for his specific watersheds and conditions. Yet results obtained from his work should be applied with caution. The physical significance of cover is not necessarily established by its statistical significance or lack of significance. For example, the density of forest cover on Watershed 172 of 43.6 ac, at Coshocton, increased in a nine-year period from ten per cent, as shown in Figure 1, to 95 per cent, as shown in Figure 2. Table 1 shows storm and watershed variables, and peak discharges for the nine-year period. The last column of Table 1 shows that the peak discharge for each year of the period did not reflect the great change in the cover variable, a greater change than occurred in any other variable. Although there is no real justification for applying the author's equation, it was used because it contained a significant cover variable. As cover increased, computed peak discharges were much less than the actual, as shown in the next to last column. Watershed 134 of 0.92 ac, representing reforested subdrainage areas, with the same increase in density of forest cover over the same period, shows the actual important effect of such cover changes per small unit of area. The units of flow used permit direct comparison. Peak discharges for Watershed 134 dropped from over twice as great, to less than one-fifth as great as those from Watershed 172, as shown in the last column of Table 1. Had the actual peak discharges been used to establish an equation for Watershed 172, increases in cover would seem to have little influence. Better cover increased permeability rates, and consequently infiltration rates, so that most of the flow of Watersbed 172 is now subsurface flow which reappears above the measuring flume. Peak discharges have not materially reduced and reflect the particular soil and geologic conditions of Watershed 172.

Table 1--Peak discharge for reforested watersheds 172 (43.6 ac) and 134 (0.92-ac)

Date	Watershed number	Watershed and storm variables[a]							Peak discharge	
		A		aP	P_{24}	P_1	Tm	C	Computed[b]	Actual
		ac	sq mi	in	in	in/hr	°F	pct	in/hr	in/hr
July 8, 1939	134	0.92	0.001	4.55	2.60	1.07	69	10	. . .	1.45
	172	43.6	0.068	4.55	2.60	1.07	69	10	0.27	.60
June 28, 1940	134	0.92	0.001	5.60	1.84	1.08	61	15	. . .	1.00
	172	43.6	0.068	5.60	1.84	1.08	61	15	0.09	0.54
May 22, 1941	134	0.92	0.001	3.98	2.41	0.99	59	20	. . .	0.77
	172	43.6	0.068	3.98	2.41	0.99	59	20	0.07	0.60
Mar. 16, 1942	134	0.92	0.001	2.04	0.73	0.38	32	25	. . . .	no record
	172	43.6	0.068	2.04	0.73	0.38	32	25	0.001	0.13
May 30, 1943	134	0.92	0.001	3.28	1.84	0.79	56	40	. . . .	0.18
	172	43.6	0.068	3.28	1.84	0.79	56	40	0.003	0.24
Apr. 8, 1944	134	0.92	0.001	1.73	1.34	0.42	35	50	. . . .	0.01
	172	43.6	0.068	1.73	1.34	0.42	35	50	0.001	0.11
Sep. 23, 1945	134	0.92	0.001	5.53	2.62	1.16	57	80	. . . .	0.07
	172	43.6	0.068	5.53	2.62	1.16	57	80	0.02	0.35
June 16, 1946	134	0.92	0.001	3.32	3.05	1.88	61	95	. . .	0.10
	172	43.6	0.068	3.32	3.05	1.88	61	95	0.03	0.72
June 6, 1947	134	0.92	0.001	5.56	1.85	1.19	64	95	. . . .	0.02
	172	43.6	0.068	5.56	1.85	1.19	64	95	0.003	0.24

[a] A is watershed area; aP is 21-day antecedent precipitation; P_{24} is maximum 24-hour precipitation; P_1 is maximum one-hour precipitation; Tm is minimum daily temperature on day of P_{24}; C is forest-cover density.
[b] By author's Eq. (1).

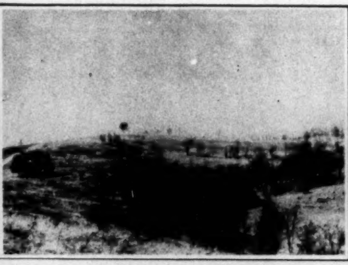
Fig. 1--Watershed 172 in 1939

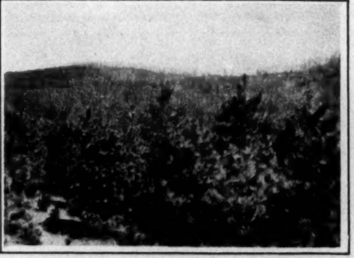
Fig. 2--Watershed 172 in 1948

When cover increases infiltration, the supply of water to both rates and amounts of surface runoff is reduced. Increased infiltration gives soil pore space a greater opportunity to fill. This may also result in a reduction of the supply of water to both rates and amounts of subsurface flow. Reductions in supplies of water to both surface and subsurface flow will result in reduced peak discharges. A special case occurs when the reduction of the supply of water to subsurface flow, through the greater use of pore space, is less than the increase in infiltration due to cover. Then subsurface flow contributions to stream flow will probably increase. Under such conditions the hydrograph show-

ing the increase in subsurface flow when synchronized with the hydrograph showing the decrease in surface runoff may result in a peak discharge less than usual, depending upon the hydrologic characteristics of the watershed. A peak discharge less than usual may be due to the shape of the subsurface hydrograph, which generally has a longer base than the surface hydrograph, as well as to the decrease in surface runoff. In some geologic areas, where subsurface flow caused by a storm does not reappear as stream flow, the cover effect which increases infiltration should always reduce flood peaks. From the standpoint of sedimentation, increases in subsurface flow is also beneficial as such flow is far less erosive than overland flow.

Peak discharges for many watersheds are composed of surface and various types of subsurface flow, changes in these amounts composing the peaks are an end result of physical activities on a watershed. These physical activities should be more completely analyzed for the physical significance of factors and their relationships. This discussion is not a criticism of the author's approach to an important social and economic problem but rather a belief that there is a need for many more analyses, by hydrologists, of a type which would yield more helpful information for such problems. It would seem that a flexible approach is desirable, using the tools that are available and that may develop, where they apply. Even when a variable is found to be significant, its actual effect on the laws involved in water and soil movements may still remain unknown. A greater knowledge of these laws would be helpful in a program of watershed management that assists nature in creating desirable hydrologic and soil balances.

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CLEAVAGE IN EAST-CENTRAL VERMONT

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Abstract--Two types of cleavage, schistosity (flow cleavage) and slip cleavage, are common in the metamorphosed sediments of east-central Vermont. Two generations of cleavage are also recognized. Cleavage of the earlier stage of deformation is schistosity, and is generally parallel to bedding. Just west of the Monroe Fault, along the eastern border of the area, only this earlier schistosity is present; farther west, a slip cleavage cuts the earlier schistosity. This slip cleavage is more and more intensely developed toward the west, and about three or four miles west of the Monroe Fault it grades without deflection into a true schistosity. This later schistosity apparently has obliterated the earlier schistosity that is presumed to have been present here. Both the later schistosity and its more easterly equivalent, the slip cleavage, are parallel to the axial planes of numerous minor folds in the rocks. The passage without deflection of slip cleavage into schistosity is taken as evidence that slip cleavage and schistosity are here mechanically equivalent. Schistosity forms in the higher metamorphic environment (staurolite zone of metamorphism in this area).

The slip cleavage is along the axial planes of tiny crinkles in the earlier schistosity. Where the crinkles become nearly isoclinal, the limbs are thinned or even sheared off against slip planes. In some places where crinkles have been sheared off on both limbs, the displacement on adjacent parallel slip planes is in opposite directions. Therefore these parallel slip planes cannot be the same as the complementary shear planes of solid deformation because such shear planes make an appreciable angle with one another. The slip cleavage described here cannot be the same as fracture cleavage, as commonly used by Leith and many others.

Two types of strain may be identified in many of the rocks with slip cleavage: (1) The crinkles between shear planes represent buckling in the rock, and shortening essentially at right angles to the slip cleavage. This buckling involves some rock flowage because the crinkles are almost perfect similar folds. (2) In most outcrops and in the area as a whole, normal-fault movement on the slip-cleavage planes predominates over reverse-fault movement. Considering large masses of rock, therefore, the rocks have also been deformed by translation that appears to be simple shear. The direction of shortening that results from this shear generally makes a highly oblique angle with the slip cleavage, and only approaches the normal to the cleavage with extreme translation.

Total deformation of the rock involves two components. One is flattening of the thin plates bounded by slip planes, and the other is distortion of the rock by simple shear along the slip planes. Using the analogy of a deck of cards, the deck is deformed by slipping between cards and also by thinning of many or all of the individual cards. Inasmuch as the slip cleavage developed here seems to grade into, and be mechanically equivalent to, schistosity, it may be permissible to extrapolate from the evidence of the slip cleavage and to suggest that the later schistosity, though involving more penetrative movement than the slip cleavage, may originate by a similar process. It is suggested that any given total deformation of rocks with schistosity may be resolvable into two components. One involves flattening of the rock by rock flowage, with formation of schistosity in the plane of flattening, as described by Leith. The other involves simple shear parallel to the plane of schistosity. If this theory is correct for this area and also has application elsewhere, many of the differences between geologists who hold that schistosity represents planes of slip and those who hold that it represents planes of flattening may be resolved.

Introduction

Two types of cleavage, schistosity, and slip cleavage (see Fig. 1) are common in the metamorphosed sediments of east-central Vermont. (The structural feature here described as "slip cleavage" was included by LEITH [1905, p. 120] in his description of various types of fracture cleavage, and the term "fracture cleavage" is now widely used for the phenomenon. A considerable part of the present paper is devoted to the evidence that slip cleavage like that of east-central

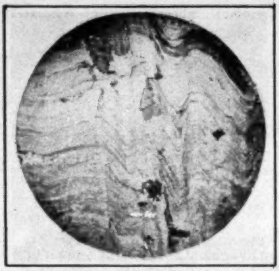

Fig. 1--Slip cleavage (vertical) cutting schistosity (crinkled); ordinary light, ×17

Vermont should not have been regarded as fracture cleavage by Leith because it has much more in common with what he called flow cleavage. The older term slip cleavage, defined below, is therefore preferable for the cleavage discussed here. It not only has priority, but also it is not encumbered with a wide variety of connotations and implications, as is fracture cleavage.) Study of the areal distribution and internal structure of rocks with slip cleavage has led to tentative conclusions that bear on the origin of the local slip cleavage, and possibly of the schistosity. These conclusions may be summarized as follows:

(1) The slip cleavage of east-central Vermont is very similar to schistosity in its angular relation to the deformation of large masses of rock.

(2) The slip cleavage of this region is not fracture cleavage in the original genetic sense of that term.

(3) Slip cleavage (and possibly schistosity) seems to be the product of two distinct types of deformation, namely, translation parallel to the cleavage planes, and flattening of the rock at right angles to cleavage. It is proposed that both types of deformation may progress simultaneously, and that each is but one component of the deformation of the rock as a whole.

The area of study (see Fig. 2) includes the western half of the Woodsville quadrangle, and the Orange County copper district [WHITE and ERIC, 1944], which covers parts of the Strafford and East Barre (Corinth) quadrangles. The Woodsville area was mapped during the summers of 1937-1939, in connection with graduate studies at Harvard University. The copper district was mapped in 1943 for the United States Geological Survey.

General geology

The eastern boundary of the area (see Fig. 2) is the Monroe Fault, which separates the rocks of Vermont from those typical of western New Hampshire [ERIC, WHITE, and HADLEY, 1941]. West of this Fault and underlying a narrow belt more or less parallel to it is a unit composed of dark to light gray slate and phyllite named the Meetinghouse slate by DOLL [1945]. The Gile Mountain schist of DOLL [1945], made up of interbedded mica schist, quartz-mica schist, and micaceous quartzite, lies west of the Meetinghouse slate. Still farther west is the calcareous Waits River formation [CURRIER and JAHNS, 1941], containing beds of impure marble and calcareous mica schist interbedded in all proportions with non-calcareous schists. On the average, about 50 per cent of the beds are calcareous.

These rocks are all older than Middle or Late Devonian and younger than Middle Ordovician, but cannot be more precisely dated on the basis of evidence now available. The Gile Mountain schist is believed to be older than the Meetinghouse slate and younger than the Waits River formation; reasons for this belief will be presented elsewhere [WHITE, in preparation].

The degree of metamorphism of the rocks increases westward. The rocks along the eastern boundary generally contain biotite. Garnet and staurolite appear a little farther west, and sillimanite is found in the Strafford and East Barre quadrangles. In the Woodsville quadrange, muscovite, biotite, garnet, and staurolite form prominent porphyroblasts. It is clear that these crystals have grown, for the most part, after all major deforming movement in the rocks had ceased. A large number of crystals are randomly oriented, and indiscriminately cut across cleavage planes and bends in the cleavage and bedding. The thermal peak of metamorphism was, therefore, post-tectonic.

The major structure of the area is revealed by the outcrop pattern of the boundary between the Waits River formation and the Gile Mountain schist (see Fig. 2). In most of the Woodsville quadrange, this boundary is fairly straight, more or less parallel to the Monroe Fault, and dips steeply east or west. Near the south end of the quadrangle, the contact turns abruptly westward, and dips gently northward. The rocks here show considerable small-scale crumpling. Farther southwest, the boundary reveals larger and larger folds, many of them almost isoclinal, and in the central part of the Strafford quadrangle, some folds have amplitudes of as much as 1 1/2 miles. Except in the southernmost part of the Strafford quadrangle, virtually all the folds in the entire area plunge to the north or northeast at angles between ten and 50°.

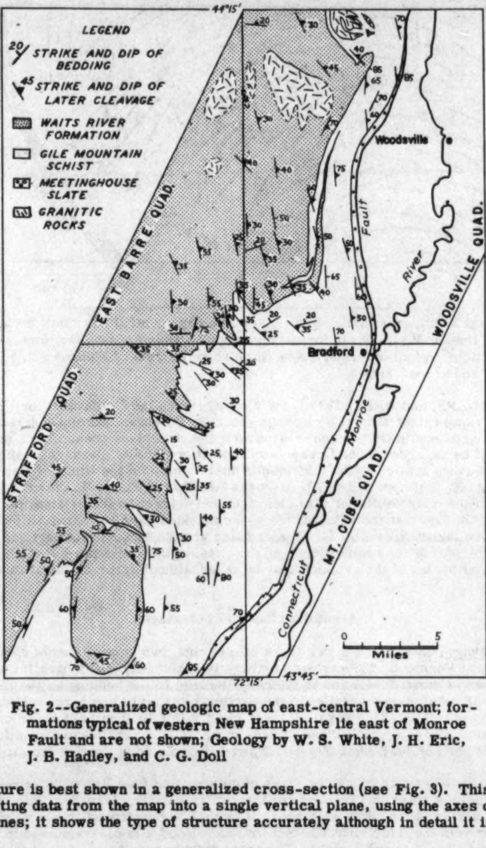
44°15'
LEGEND
20 STRIKE AND DIP OF BEDDING
45 STRIKE AND DIP OF LATER CLEAVAGE
WAITS RIVER FORMATION
GILE MOUNTAIN SCHIST
MEETINGHOUSE SLATE
GRANITIC ROCKS
EAST BARRE QUAD.
STRAFFORD QUAD.
WOODSVILLE QUAD.
MT. CUBE QUAD.
Woodsville
Bradford
Monroe Fault
Connecticut River
0 5
Miles
72°15'
43°45'

Fig. 2--Generalized geologic map of east-central Vermont; formations typical of western New Hampshire lie east of Monroe Fault and are not shown; Geology by W. S. White, J. H. Eric, J. B. Hadley, and C. G. Doll

The structure is best shown in a generalized cross-section (see Fig. 3). This section was made by projecting data from the map into a single vertical plane, using the axes of minor folds as projection lines; it shows the type of structure accurately although in detail it is diagrammatic.

Character of cleavages

Cleavage of two general types is present in the area. Schistosity is present in all of the argillaceous rocks, and some rocks also have a slip cleavage that cuts schistosity (see Fig. 1).

The schistosity of east-central Vermont is the same as flow cleavage, as defined by LEITH [1905, pp. 23 and 99]. It is due to parallelism of all or a majority of the micaceous elements in the rocks. Isolated mica plates show this orientation as well as the plates that are grouped in micaceous layers (foliation planes) in the rock. In addition, the schistosity is generally defined by the dimensional elongation of quartz and calcite grains.

Dale's term slip cleavage [PUMPELLY, WOLFF, and DALE, 1894, pp. 139-158, Fig. 34, 41-46, 53-54, 57; DALE, 1898, p. 209] is used for a second direction of splitting, transverse to schistosity, that is present in many of the schistose rocks. (In most of the figures referred to

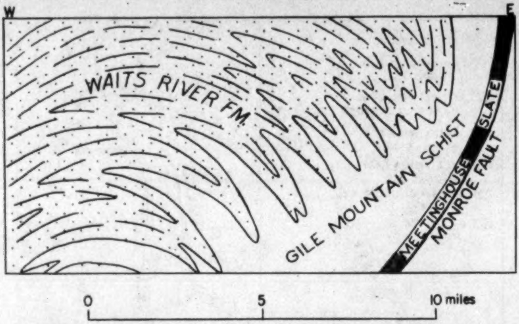

Fig. 3--Diagrammatic vertical section, east-central Vermont; broken lines in Waits River formation suggest attitude of bedding; formations typical of western New Hampshire lie east of Monroe Fault and are not shown

[PUMPELLY, WOLFF, and DALE, 1894], the cleavage is called "cleavage" or "cleavage foliation" (transverse cleavage) rather than slip cleavage, because Dale was more concerned here with its relation to bedding than with its physical character. But it is clear from a later paper [DALE, 1896, p. 570] that he regarded these figures as illustrations of slip cleavage.) As used by Dale, the term, slip cleavage applies to the microfaults that develop on the limbs of tiny crinkles in foliate rocks [DALE, 1896, pp. 566-567]. In rocks like that of Figure 1, the crinkles are essential to development of the microfaults, or slip cleavage, and determine the orientation of this cleavage. This is shown by the fact that the axial planes of the crinkles have the same attitude, whether or not their limbs are faulted (see Fig. 1). The crinkles are the independent part and the slip cleavage the dependent part of the phenomenon. In practice, in the rocks here described, the average attitude of the axial planes of the crinkles may be taken without error as the attitude of the slip cleavage.

Areal distribution of cleavages

Earlier cleavage--In addition to two types of cleavage, two generations of cleavage are present in east-central Vermont. The earlier cleavage is schistosity. It is parallel to the axial planes in the noses of minor folds, and is typically parallel to the bedding on the limbs. Inasmuch as minor folds with axial planes parallel to the earlier schistosity are rare, schistosity is parallel to bedding in most outcrops. This parallelism is rigid within the limits of error of careful megascopic observation. The earlier cleavage strikes more or less parallel to formation boundaries, and has therefore been omitted from Figures 2 and 4 to avoid complicating the diagrams.

Later cleavage--Cleavage of a later stage of deformation (see Fig. 4) is present or dominant in most of the area, and transects or even obliterates the earlier cleavage. This later cleavage typically strikes northwest and dips northeast. It is rare in outcrops within a mile of the Monroe Fault, but farther west the later cleavage is a well-developed slip cleavage, and in most of the western part of the area it is schistosity. The areal distribution, trend, and character of this later cleavage (that is, whether slip cleavage or schistosity) in the Woodsville area is shown in Figure 4. In the copper district to the west and southwest, the later cleavage is everywhere schistosity.

The boundary between the area of slip cleavage and the area of later schistosity more or less follows the eastern border of the staurolite zone of metamorphism. A controlling factor in the formation of a later schistosity, in preference to slip cleavage, may be high temperature.

The westward transition from slip cleavage to later schistosity is gradual. Study of rocks from the zone of transition suggests that the later schistosity has formed in part by mechanical rotation and smearing out of the earlier schistosity, and in part by the growth of new mica flakes oriented parallel to the later cleavage.

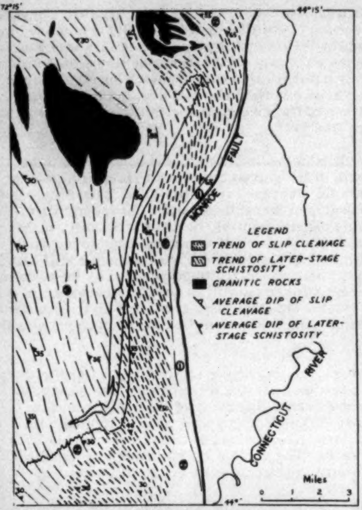
72°15'
44°15'
44°
MONROE FAULT
CONNECTICUT RIVER
LEGEND
TREND OF SLIP CLEAVAGE
TREND OF LATER-STAGE SCHISTOSITY
GRANITIC ROCKS
AVERAGE DIP OF SLIP CLEAVAGE
AVERAGE DIP OF LATER-STAGE SCHISTOSITY
Miles
0
1
2
3

Fig. 4--Trend of later-stage cleavage, western part of Woodsville quadrangle, Vermont; stratigraphic units designated by numbers in circles as follows (1) Meetinghouse slate of Doll; Gile Mountain schist of Doll; and (3) Waits River formation

The result of mechanical rotation of the earlier schistosity is evident in the crinkles of Figure 5. On the limbs of the crinkles next to the actual slip planes, the rotated earlier schistosity approaches the attitude of the slip cleavage. Only a small percentage of the rock in Figure 5 is made up of mica parallel to the slip cleavage. But in rocks that display more intense development of slip cleavage, the crinkles are more acute, and the rock, as viewed normal to the axes of crinkles, is made up of a series of relatively wide bands of parallel mica (cleavage bands) separating narrow septa in which the micas curve around in the noses of crinkles. The limbs of the crinkles seem to have increased in width at the expense of the noses, as more and more of the older schistosity was rotated into parallelism with the limbs. The end product of this increase would be a rock in which the noses have been completely smeared out, or reduced to less than the width of a single mica flake; the whole rock would be made up of limbs and all the mica would be oriented parallel to the slip cleavage. The later schistosity of the rocks in the western part of the area may have originated in part, at least, by such mechanical enlargement of the limbs of crinkles at the expense of the noses.

Growth of new mica oriented parallel to the slip cleavage has also played a part in the formation of the later schistosity. New micas that have grown on the limbs of crinkles are parallel to and difficult to distinguish from the older flakes. But in specimens from the west edge of the area of slip cleavage, new micas, oriented parallel to the slip cleavage, may be seen to cut the older schistosity in the noses of crinkles. These micas, which may be isolated flakes, have formed in response to more penetrative deformation of the rock than the relatively discontinuous deformation that produced the slip cleavage. Growth of these new micas at the expense of the older micas in the noses of crinkles may have been as effective as mechanical rotation and smearing, described above, in obliterating traces of the earlier schistosity in the western part of the area.

Equivalence of slip cleavage and schistosity

The most significant feature of the transition between slip cleavage and later schistosity is the fact that on both a regional scale (see Fig. 4) and in individual thin sections the later schistosity is essentially parallel to the slip cleavage. There is no appreciable or consistent deflection of cleavage as it passes from slip cleavage to schistosity. In east-central Vermont, therefore, both slip cleavage and later schistosity seem to form with a similar, if not identical, angular relationship to the principal axes of the later stage of deformation. This suggests that, with respect to the gross deformation of the rocks, slip cleavage and the later schistosity are mechanically equivalent.

Slip cleavage versus fracture cleavage

Whether or not slip cleavage is fracture cleavage depends on what is meant by the latter term. LIETH'S [1905, p. 12] original statement on fracture cleavage is as follows: "Fracture cleavage is conditioned by the existence of incipient, cemented, or welded parallel fractures and is independent of a parallel arrangement of the mineral constituents."

Insofar as the rock actually splits or cleaves on the microfaults, the definition, taken literally, is applicable to the slip cleavage of east-central Vermont. But where there are cleavage bands of well-oriented mica along the microfaults (see Fig. 5), these will form as effective a cleavage as the microfaults. If the latter are cemented or welded, the cleavage bands may be more effective.

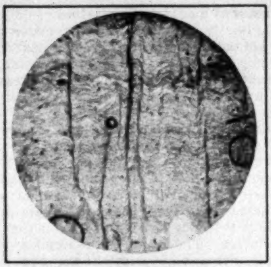

Fig. 5--Slip cleavage (vertical) cutting schistosity (crinkled); ordinary light, X 17

It seems inappropriate to use the term fracture cleavage for a direction of splitting that is actually determined in large part by the orientation of micas in cleavage bands. Because the rock may cleave along the limbs of crinkles whether or not there was ever an actual break, the term has come to be misused; one can find, in the literature, illustrations of fracture cleavage that show rocks with no fractures whatever.

The ultimate basis of the cleavage should also be considered. The original definition of fracture cleavage states that the cleavage, or ability to be split, should not be dependent on mineral orientation. Granting that the cleavability depends entirely on the microfaults, if the microfaults follow zones of weakness determined by the oriented micas on the limbs of crinkles (see Fig. 1 and 5), the cleavage also is indirectly determined by the parallel arrangement of minerals. It is actually dependent, ultimately, on the fact that there is a parallel arrangement; otherwise one might expect to find the fractures as commonly in the nose as on the limbs of a crinkle.

The implications of the term fracture cleavage should also be considered here. Despite the fact that some writers have properly made it clear that they use the term only in the sense of the definition quoted above, it is almost impossible to avoid conveying many of the implications of Leith's views on the origin of fracture cleavage (that is, Van Hise's views on fissility) when the term is used. These views have been reiterated in many standard texts, both American and European, and have become firmly attached to the term. These genetic implications of fracture cleavage do not apply to the slip cleavage of east-central Vermont, as shown by the following.

As conceived by Leith, fracture cleavage forms on one or both of the potential shear planes in a stressed rock. These two sets of shear planes have opposite directions of displacement, and, as shown by geologic, experimental, and theoretical evidence, intersect one another at appreciable angles. If they originate in the prescribed manner, fracture-cleavage planes with opposite directions of displacement should make a measurable angle with one another. Figure 5 shows clearly that closely spaced slip-cleavage planes with opposite directions of displacement may be remarkably parallel to one another, and may converge or diverge with respect to the apparent direction of movement of the included septum. Their orientation must differ appreciably from the orientation of the theoretical shear planes in the stressed rocks as a whole, even assuming that the rock was far from brittle. Fracturing on the theoretical shear planes of the stressed rock as a whole does not seem to be the primary cause of the location and orientation of the slip cleavage.

Secondly, as originally described, fracture cleavage and cleavage due primarily to parallel orientation of elongate or platy minerals differ from each other in their angular relations to axes of deformation [LEITH, 1905, p. 125]. Fracture cleavage, so distinguished, should show a change in attitude if it grades into cleavage defined by mineral orientation. Evidence has been presented that in east-central Vermont slip cleavage transecting an earlier schistosity in part of the area (see Fig. 1 and 5) grades westward without deflection into a later schistosity (see Fig. 4).

Thirdly, the slip cleavage of east-central Vermont is far more a flowage than a fracture phenomenon. It is evident from Figures 1 and 5 that the crinkling may or may not be accompanied by actual rupture along the limbs. The microfaults, or slip-cleavage planes, appear to be an end-product of the process, and fundamentally dependent on the crinkling for their genesis, location, and orientation. The formation of crinkles such as those illustrated here must be accompanied by appreciable rock flowage. Even in the crinkles with ruptured limbs, there is considerable bending that is independent of the rupture, and the limbs of all the more nearly isoclinal crinkles are noticeably thinned. A large part of the whole process leading to the formation of slip cleavage seems to be characterized more by flowage than by fracture.

In summary, it is questionable that slip cleavage is entirely independent of mineral orientation. Secondly, it is difficult to divorce entirely the genetic implications of the term fracture cleavage from its descriptive use, despite careful definition, and the slip cleavage here seems to be formed in a different manner from the classical fracture cleavage. Fracturing on the theoretical shear planes of the stressed rock as a whole does not seem to be the primary cause of the localization and orientation of the slip cleavage. And, lastly, use of fracture cleavage for the structural feature here called slip cleavage places undue emphasis on one aspect of this planar element, whereas actually there is clear evidence of appreciable flowage in the process leading to its formation. For these reasons it seems inappropriate to use the term fracture cleavage for the slip cleavage discussed here, even though the term is commonly so used on the authority of the original description [LEITH, 1905, p. 120]. One cannot state the matter as simply as to say that slip cleavage is not fracture cleavage, but there are valid grounds for preferring not to use fracture cleavage here.

Origin of slip cleavage

The regional habit and microscopic elements of the slip cleavage of east-central Vermont provide clues to its origin. On a regional scale, a majority of the slip-cleavage planes of the western part of the Woodsville quadrangle show normal fault movement, that is, the northeast or hanging-wall side of such slip planes has dropped with respect to the footwall side. This direction of displacement is in harmony with the pattern of practically all the later minor folds in the area of slip cleavage; these minor folds, interpreted as drag folds [BILLINGS, 1942, p. 81], also indicate that rocks on the northeast have moved downward with respect to rocks on the southwest. (The minor folds referred to here are not the tiny folds or crinkles of Figures 1 and 5, but the typical minor folds a few inches to a few feet across that are seen in outcrops.) These folds are nearly perfect similar folds, and the slip cleavage is parallel to their axial planes. They satisfy the geometric requirements for slip or shear folds [KNOPF and INGERSON, 1938, pp. 157-159; CLOOS, 1937, pp. 56-57]. A considerable part of the total deformation of the rocks may be reasonably ascribed to small increments of slip on countless tiny slip planes.

Another component of the total deformation is revealed by microscopic study of the slip cleavage. The tiny crinkles between slip planes (see Fig. 1 and 5) suggest shortening of the rock essentially at right angles to the slip cleavage. Shortening cannot be assumed, however, because some types of fold (for example, shear or card-deck folds) can form without shortening normal to their axial planes. Careful measurements were made on an enlarged tracing of a thin-section showing tiny crinkles between slip-cleavage planes or bands (Fig. 1 shows a small part of this section). The distance between certain layers was measured parallel to the slip planes at a number of places. This distance is essentially constant in all parts of a crinkle between two slip planes or cleavage bands. But it is considerably greater than the distance between the same layers, measured in the same direction, in a part of the section that has no crinkling (for example, left side of Fig. 1). There has, therefore, been pronounced elongation of parts of the rock parallel to the slip planes and thinning of these parts in a direction essentially perpendicular to the slip planes. This must have been accomplished by actual rock flowage in addition to buckling because the deformation was essentially continuous; there are few breaks in the smooth curves of the anticlines and synclines. The amount of thinning is not the same in all septa between slip planes, and is greatest in those septa that contain the most nearly isoclinal crinkles. But in general, insofar as any individual thin septum is concerned, there has been thinning of the rock essentially at right angles to the slip planes.

The total deformation of the rock, therefore, must be measured in terms of two entirely separate components. One is the aggregate displacement along all the slip planes in a given unit of rock. The other reflects the shortening at right angles to slip-cleavage planes, which is primarily a flowage phenomenon. The duality of the process may be illustrated by the familiar example of a deck of cards; the cards used here must be made of a plastic substance. The slip component of deformation is accommodated by displacement along the surfaces between the cards; the shortening component of deformation is illustrated by squeezing and thinning of some or all of the individual cards. A similar mechanism of deformation has been illustrated by CLOOS [1947, p. 902-904, Fig. 18] in connection with his study of the distortion in folds.

It is suggested that under certain conditions slip cleavage may form more or less at right angles to the direction of principal shortening in the rock as a whole (see Fig. 5). Insofar as there is also slip preponderantly in one direction along individual slip planes, however, the cleavage may depart from a position normal to the axis of total shortening. Under different conditions, therefore, slip cleavage may be either normal or oblique to the axis of maximum total shortening in any given unit of rock.

Application to schistosity

The later schistosity of rocks in the western part of the area grades eastward without deflection into slip cleavage, and on this basis is assumed to have a mechanical significance similar to that of the slip cleavage. If schistosity, like slip cleavage, actually is the combined result of both slipping parallel to cleavage and shortening normal to the cleavage, the present diverse views on the origin of cleavage may be resolvable. As CLOOS [1947, p. 904] points out, a given deformation generally cannot be analyzed in terms of either simple shear or flattening alone, but must be analyzed in terms of both.

Acknowledgments--I am much indebted to M. P. Billings of Harvard for his counsel and valuable suggestions in the Woodsville study. I gratefully acknowledge my debt to J. H. Eric of the United States Geological Survey, who worked with me in both areas, and to R. H. Jahns and J. B. Hadley of the Survey for many stimulating discussions of the regional structure. The content of this paper has been critically reviewed by A. E. J. Engel, R. S. Cannon, Jr., Earl Ingerson, J. H. Eric, and C. A. Anderson of the United States Geological Survey, and although I have profited from their suggestions, I must accept full responsibility for the conclusions presented. R. M. Denning of the Michigan College of Mining and Technology generously gave his time in the preparation of the photomicrographs.

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EARTHQUAKE STUDY IN SOUTHERN CALIFORNIA, 1948

B. Gutenberg, C. F. Richter, and H. Benioff

(Contribution No. 490, Balch Graduate School of the Geological Sciences,
California Institute of Technology, Pasadena, California.)

This continues the previous report by GUTENBERG and RICHTER [1947].

S. K. Chakrabarty of Bombay was in residence at Pasadena for most of 1948. In October, 1948, R. E. Ingram of the National University, Dublin, arrived for an academic year of study and research. A. Due-Rojo of Cartuja, Spain, W. Heiskanen of the Isostatic Institute, Helsinki, and R. Stoneley of Cambridge, England were also visitors for more or less extended periods, and provided much valuable material for discussion and investigation.

Ivan Tolstoy spent several days searching the seismograms for evidence of SOFAR waves originating from submarine earthquakes. Several small examples were found. A much larger one has since been identified on records of the earthquake of January 23, 1938, off Hawaii.

B. Gutenberg attended the Oslo meeting of the International Geophysical Union. A paper on earthquakes and structure of the Earth's crust was presented to a joint meeting of several Associations. He also presented a paper, Unexplained Phases in Seismograms, which has been submitted to the Bulletin of the Seismological Society of America. Three groups of waves, following P after about five, ten, and 20 sec on seismograms of deep-focus earthquakes recorded at Huancayo, are possibly waves transformed from longitudinal to transverse at depths of roughly 40, 80, and 150 km. Others may be reflected at a depth between 900 and 1000 km., where there may be a sudden small decrease in velocity.

A paper by C. F. Richter on the history and applications of the magnitude scale was read at Oslo by B. Gutenberg and will appear in the proceedings.

Other contributions in course of publication are:

By S. K. Chakrabarty: The theory of electromagnetic seismographs, submitted to the Bulletin of the Seismological Society of America. This paper arose from experience and discussions in connection with the testing of a Benioff instrument destined for use in India.

By S. K. Chakrabarty and C. F. Richter: The Walker Pass earthquakes and structure of the southern Sierra Nevada, also submitted to the Bulletin of the Seismological Society of America. The principal earthquake of March 15, 1946 is assigned a depth of 21 km, with an epicenter definitely within the Sierran block. The epicenters of aftershocks scatter about this, with no definite alignment. Some of the aftershocks are better suited by the more usual depth of 18 km. The effect of the "shadow" of the root of the Sierra Nevada appears on the records at Tinemaha, to the north.

By B. Gutenberg: The structure of the Earth, published in Scientia; New data on the lower stratosphere published in the Bulletin of the American Meteorological Society; Approximations in geophysics published in Publications of the Finnish Geodetic Institute; and a paper on the relation of geophysics to general physics and geology, published in Physics Today.

By B. Gutenberg and C. F. Richter: Erdbebengeographie und Dynamik der Erdkruste published in Die Naturwissenschaften: A French translation will appear in the publication of the International Seismological Association. This is an expanded version of the concluding section of the book, "Seismicity of the Earth and associated phenomena" by the same authors, now in press (Princeton University Press).

H. Benioff is continuing his investigations on the relation of earthquake and aftershock sequences to rock creep. On the basis of the elastic rebound theory, the fault rock strain relief which produces an earthquake is proportional to the square root of the energy. Consequently in a sequence derived from a single fault system the square root of the energy of each shock represents a strain release (or increase) increment, and a plot of the accumulated sum of such increments against time represents the creep curve of the fault rock. The energy is derived from the magnitudes of the shocks as determined by Gutenberg and Richter. In the case of aftershock sequences, it has been found that the creep curves exhibit either simple compression elastic creep release characteristics or compression elastic creep release followed by shear elastic creep release.

The magnitude data for the earthquake sequences have been taken from tabulations by Gutenberg and Richter in their forthcoming book. Study of a number of these sequences occurring in all the active regions of the world has revealed that most of them form creep series. Many types of creep are represented, such as constant velocity, exponential velocity, elastic and elastic flow. Individual sequences may have linear extents of 20° to 30° of latitude as in the case of the South American and Tonga sequences and the evidence strongly suggests that they behave as single mechanical units. The very deep focus Tonga sequence exhibits elastic creep which continued some 25 years, thus demonstrating that at depths of 650 km rock masses can support creep stresses for many years.

Instrumental development under Benioff may be summarized as follows:

In the older standard models of the variable reluctance seismographs the transducers were assembled with silicon steel laminations which had not been heat treated. Recent experiments have demonstrated that heat treatment of the laminations, after punching, greatly improves the damping characteristics of the pendulum and at the same time reduces hysteresis effects to negligible quantities.

Work is progressing on a group of moving coil electromagnetic pendulum seismographs having short period galvanometer film recorders for semi-permanent seismograph stations. One unit is already in service with paper recording at Desert Hot Springs.

A modified Michelson tide gauge is being constructed for the measurement of a secular tilt. This instrument uses a twenty-meter glass tube half filled with mercury. At either end the tube enters a three inch cylindrical container in which a pool of mercury is formed. The ground tilt is determined by measuring the relative height of the two pools of mercury. This measurement is accomplished electrically by comparing the electrostatic capacities of the two condensers formed by the pool surfaces and fixed metallic plates mounted above each pool.

A device is being constructed for observing the creep behaviour of rock samples subjected to compression and shear stress simultaneously.

A study of microseisms is being supported and sponsored by the Geophysical Research Directorate of the Cambridge Field Station, AMC, U. S. Air Force.

S. T. Martner has completed a thesis on observations of seismic waves reflected at the Earth's core. The observed amplitudes of PcP are found to be larger than those calculated, especially in the horizontal components. Amplitudes of ScS agree more closely with those calculated, assuming zero rigidity for the core. A similar investigation for P′ and other waves through the core has been initiated by M. E. Denson. The amplitude ratio of pP/P is being investigated by H. M. Mooney, the type of motion in S-waves in seismograms of local shocks by Dehlinger, and of teleseisms by Ingram.

B. F. Howell, Jr. has completed a thesis on ground vibrations near explosions. He finds that several types of surface waves can be identified at short distances; one of these has the properties of Rayleigh waves, with forward orbital motion of the displaced particle, while another has retrograde motion (as observed by Leet).

In cooperation with J. P. Buwalda, the field geology of the area of the Manix earthquake of 1947 is being investigated for the purpose of interpreting the instrumental findings. This has been much facilitated by a beautiful series of air photographs supplied by the Army Air Force.

On December 4, 1948, at about 23:43:17 GCT, an earthquake of magnitude 6.6-6.7 originated near 33°55′ N, 116°28′ W, probably on the San Andreas fault or the closely adjacent Mission Creek fault. Field parties led by F. E. Lehner operated a portable seismometer unit at four localities within a few miles of the epicenter, beginning within eight hours. A few days later a temporary station for continuous recording with a Benioff vertical instrument was established at Desert Hot Springs, the nearest community, with the cooperation of Mrs. L. Johnson and the local Chamber of Commerce. The station coordinates are: 33°57.7′ N, 116°30.0′ W, h = 335 meters. A number of aftershocks were recorded simultaneously at this station and by the portable unit at another nearby location. The data on the entire shock group are unusually copious, and should yield exceptionally good results on depth of focus, wave velocities, and crustal structures. The nearest points of observation, including Desert Hot Springs, show the abnormally short apparent S-P interval of 1 1/2 sec or less commonly observed in similar circumstances, which is not yet satisfactorily explained. Other points only a few kilometers farther away show a true $\bar{S}$-$\bar{P}$ of three to four seconds.

On May 21, 1948, at 15:38:20 GCT a shock of magnitude 4.8 occurred at 33.0°N, 123.5°W. This is far off the coast beyond the steep submarine slopes which mark the edge of the continental topography. Only two similar shocks are known, in 1933 and 1940, from widely separated epicenters. It is possible that these three epicenters are actually outside the continental structures and in the Pacific basin but the boundary in this sector is not precisely known.

Two shocks of magnitude 7 3/4 or over occurred during 1948; on January 24, 17^h, in the Philippines ($M = 8$) and on September 8, 15^h, in the Tonga Islands ($M = 7\ 3/4$).

The Laboratory has undertaken to report data for large earthquakes through the communication channels of the United States Navy for use in preparing warning of possible destructive tsunamis. This warning service operated on the occasion of the shock of September 8, 1948.

Routine bulletins for teleseisms and the larger local shocks have been prepared through June 1948. Reports giving epicenters and origin times for the smaller local shocks have been issued through September 1948. Provisional readings for the Pasadena station are being circulated by air letter to a short list of addresses, chiefly those of stations which are similarly reporting their data in exchange.

A special issue of Engineering and Science Monthly, published by the California Institute of Technology Alumni Association, contained articles describing the activities of the Division of the Geological Sciences. Those describing seismological work are included in the following list of publications:

Hugo Benioff: Seismological instruments developed at California Institute of Technology published in *Engineering and Science Monthly*, v. 11, pp. 24-25, 31, 1948.

J. P. Buwalda: Geologic faulting in Southern California published in *Engineering and Science Monthly*, v. 11, pp. 15-18, 1948; and Unusual opportunities for training in geophysics at California Institute of Technology published in *Engineering and Science Monthly*, v. 11, p. 10, 1948.

Beno Gutenberg: A geophysicist X-rays Mother Earth published in *Engineering and Science Monthly*, v. 11, pp. 19-20, 1948; Geophysics in war and peace published in *Transactions* of the American Geophysical Union, v. 29, pp. 155-156, 1948; and On the layer of relatively low wave velocity at a depth of about 80 kilometers published in the *Bulletin* of the Seismological Society of America, v. 38, pp. 121-148, 1948.

Beno Gutenberg and C. Y. Fu: Remarks on multiple reflections published in *Geophysics*, v. 13, pp. 45-48, 1948.

Beno Gutenberg and C. F. Richter: Earthquake study in Southern California, 1947 published in the *Transactions* of the American Geophysical Union, v. 29, pp. 406-407, 1948; and Deep focus earthquakes in the Mediterranean region published in *Geofisica pura e applicata*, Milano, v. 12, pp. 130-133, 1948.

S. T. Martner: The Dominguez Hills, (California) earthquake of June 18, 1944, published in the *Bulletin* of the Seismological Society of America, v. 38, pp. 105-119, 1948.

C. F. Richter: International recovery in seismology published in *Scientific Monthly*, v. 66, pp. 67-70, 1948.

C. F. Richter and J. M. Nordquist: Minimal recorded earthquakes published in the *Bulletin* of the Seismological Society of America, v. 38, pp. 257-261, 1948.

H. O. Wood: A possible layer for the transmission of fast P waves from surface disturbances published in the *Bulletin* of the Seismological Society of America, v. 38, pp. 33-39, 1948.

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Transactions, American Geophysical Union Volume 30, Number 4 August 1949

REPORT OF THE COMMITTEE ON INFILTRATION, 1947-1948

G. W. Musgrave, Chairman

Joel Fletcher
W. O. Smith
V. S. Aronovici
S. W. Jens
V. C. Fishel
Russell M. Cornell
H. S. Riesbol
A. L. Sharp
M. R. Lewis

The Committee has earlier noted the need of a more complete analysis of the problem of infiltration, and in continuation of previous efforts along these lines, is presenting two papers for discussion. They are "Some Properties of Water Solutions that Influence Infiltration," by Joel E. Fletcher, and "Pedological Relations of Infiltration Phenomena," by W. O. Smith, and are published with the papers in this issue of the Transactions.

REPORT OF THE COMMITTEE ON GROUND WATER, 1946-1948

S. W. Lohman, Chairman

1948	1949	1950
H. F. Blaney	C. E. Jacob	R. M. Leggette
E. B. Burwell, Jr.	Roger Rhoades	A. C. Swinnerton
G. W. Musgrave	N. A. Rose	C. K. Wentworth

No report of the Committee was prepared for the fiscal year 1946-1947, so the present report covers the two-year period July 1, 1946 through June 30, 1948. Because of space limitations, this report covers only items of research that have come to the attention of the Chairman. Reports on Hydrology and physiography of limestone terranes, by A. C. Swinnerton, and on The relation between comsumptive use of water and free-water accretion below the root zone, by G. W. Musgrave, are given as Appendices A and B respectively.

Early in 1948 the late O. E. Meinzer, then President of the Union, asked your Chairman to take over his duties as Chairman of the Subcommittee on Ground Water of the General Committee on Research of the Society of Economic Geologists, with a view of combining the work of both Committees dealing with the same subject and thus avoiding duplication of effort. The aims and organization of the General Committee have been described by the Chairman, C. H. BEHRE, JR., [1947] In his first report of this Subcommittee, MEINZER [1947] outlined nine topics in the field of groundwater hydrology on which he especially recommended additional research. On each of these topics qualified workers have signified their willingness to prepare reports indicating (1) work already done, (2) work in progress, (3) additional work that should be done, and (4) methods of implementing the additional work, listing institutions or individuals that might do the work or finance it, as follows:

(1) Hydraulics of ground water: C. E. Jacob
(2) Physics of soil moisture in relation to ground-water recharge, discharge, and storage: W. O. Smith
(3) Artificial recharge: Fred H. Klaer, Jr.
(4) The geophysics of ground-water head and runoff: M. L. Brashears
(5) Geophysical methods of exploration: Robert E. Bennett
(6) Geologic texture and structure in relation to ground water: H. E. Thomas
(7) Geochemistry of ground water: John D. Hem
(8) Salt-water balance: Chester K. Wentworth
(9) Bacterial and industrial pollution of ground waters, and the purifying capacities of rocks: Carl Wilson and Claude E. Zobell

Reports on the above topics will be published in Economic Geology as they are completed. Meanwhile, anyone having pertinent suggestions or data regarding any of these topics is asked to communicate with the men listed above or with S. W. Lohman, Chairman.

Joseph F. Poland (U. S. Geological Survey, California)--The subsidence of the land surface in the San Jose area, which is associated with the lowering of water level, has been the subject of a preliminary report [Trans. Amer. Geophys. Union, 1940, pp. 23-35] indicating that by 1937 maximum subsidence at San Jose was 5.57 ft. The investigation is continuing as a research project of the Geological Survey. The United States Coast and Geodetic Survey has releveled the control net in the Santa Clara Valley as of January 1948. This is the tenth releveling but the first since the spring of 1940. Field results are not yet available.

In the Delano area of Tulare and Kern counties in the San Joaquin Valley, a subsidence of similar magnitude has developed [Trans. Amer. Geophys. Union, 1941, pp. 40-42]. At the suggestion of the Geological Survey, the U. S. Coast and Geodetic Survey began the establishment of a control net in the Delano area in March 1948, which can be releveled in subsequent years, to afford a comparison between change in ground-water level and change in land surface.

S. W. Lohman (U. S. Geological Survey, Colorado and Wyoming)--Attempts are being made to govern the duration of field pumping tests of wells in unconfined aquifers by the length of time required for reasonably complete drainage of the dewatered part of the aquifer. Graphical determinations of the coefficient of transmissibility and the specific yield are made by the Thiem method at convenient intervals (generally 6, 12, or 24 hours) during pumping tests, and values of the apparent specific yield thus obtained are plotted against the time since pumping began. The apparent value increases with time of pumping (and with time of drainage of the dewatered material) and approaches the true value asymptotically when the dewatered material is nearly completely drained. When pumping can be continued sufficiently long, reliable values of both S and T are obtainable. The length of time required may range from a few days for coarse, well-sorted highly permeable gravel to several weeks or more for fine-grained, poorly sorted material, and reasonably complete drainage may not be obtainable at all in some fine-grained materials.

Gerald G. Parker (U. S. Geological Survey, Florida)--The staff of this office has been, and still is, engaged in research bearing on the Ghyben-Herzberg principle as applied to salt-water encroachment in aquifers of this area; on the rates of movement of salt water under pumping influences; on recharge to and discharge from limestone aquifers under varying conditions of rock formation, evapotranspiration, ground- and surface-water runoff, pumping, and related factors. Large-scale pumping tests (5,000,000 gpd per well) were made in 1947 to determine hydrologic characteristics of the aquifers. The data are interpreted in a comprehensive report now in preparation on Geology and water resources of southeastern Florida, for publication by the Florida Geological Survey.

Fred H. Klaer, Jr. (U. S. Geological Survey, Indiana)--On January 14, 1948, the aims of the cooperative research project by the Purdue University School of Civil Engineering, the Indiana Department of Conservation, and the U. S. Geological Survey were revised to include (1) the preparation of a summary report on artificial recharge, including an annotated bibliography of published information, and, insofar as is practicable, summary reports on existing recharge operations on which no published data are available; (2) consideration of investigating the ground-water phases of the heat-pump cycle; and (3) runoff and infiltration studies of a small drainage basin, with special reference to artificial disposal of excess water. The purpose of the research is to obtain information that will be of practical value to the citizens of Indiana and to the general public.

M. I. Rorabaugh (U. S. Geological Survey, Kentucky)--Studies were made along the Ohio River northeast of Louisville to determine the quantity of ground water that might be developed by induced infiltration from the river. A detailed pumping test was made on the river bank. Equations were derived for determining the hydrologic constants (transmissibility and distance to the line source). Analysis of test data included graphical determination of corrections for barometric changes, for effects of river-level changes on water levels, for screen loss in observation wells, for changes in pumping rate, and for changes in normal flow in the aquifer. Temperature measurements were made at five-foot intervals of depth in each observation well at various times during the test. Sections showing temperature distribution in the aquifer for each set of readings were of great help in determining that river water was entering the aquifer, and in tracing the flow of water from the river to the well.

Data have been collected at a Ranney collector located on the river bank southwest of Louisville. Analysis is now being made of the relation between river elevation, river temperature, pumping level, discharge temperature, and rate of discharge of the unit.

Wilbur T. Stuart (U. S. Geological Survey, Upper Michigan)--A better method is being sought for locating permeable ground-water courses in the glacial overburden of the northern peninsula of Michigan, in the hope that such water can be diverted or intercepted and thus prevented from reaching mining areas where it creates hazards and expensive mine-drainage problems.

Consideration is being given to the use of radioactive tracer compounds that could be introduced up-gradient from critical areas. The area would be traversed in plan using a Geiger counter and vertically by running gamma-ray logs in test holes. The compounds would have to be used in concentrations sufficient to be detected through 100 ft of drift and yet not exceed concentrations that would be harmful to life or excessive in cost.

E. S. Asselstine (U. S. Geological Survey, upstate New York)--Research carried out in connection with county-by-county investigation of ground-water resources during 1947 consisted of (1) the more precise delineation for buried preglacial channels in several counties and (2) a study of the effects of solution on the Devonian and upper Silurian carbonate rocks in Schoharie County. Valley profiles showing the bedrock surface have been prepared for a number of locations in Broome and Washington Counties, based on well records and geophysical data collected by the Geological Survey.

The preglacial courses of the lower Mohawk River and of other streams passing through the Albany-Schenectady area have been located more accurately than heretofore by means of well data. Regarding the hydrology of the limestone terrane, a study has been undertaken which involves certain relations between the structural features of the rock formations and the occurrence and movement of grou water, and the occurrence of caves and springs. It is expected that several reports covering these studies will be published.

Edward J. Schaefer (U. S. Geological Survey, Ohio)--The research work in Ohio pertains to studies of stream infiltration to glacial aquifers. This is particularly true of the work at Canton, Ohio, in the valley aquifers bordering Middle and West Branches of Nimishillen Creek, where the largest portion of the total infiltration is received from stream flow.. The investigations in those areas include direct measurement of losses in stream flow by gaging the streams at intervals, and comparison of flow-duration curves of these streams with other nearby streams traversing areas of similar geology, topography, and climatic conditions and not affected by ground-water pumping. By direct measurement at intervals along Middle Branch infiltration rates caused by ground-water pumping have been found to vary from 350,000 to as much as 3,600,000 gallons per day per acre of stream bottom, depending on the stage of the stream and the position of the water table. Much higher rates of infiltration undoubtedly occur in flood periods, but losses in those periods are hard to detect by direct measurement because at such times the pumpage is equivalent to only a minor portion of the total flow.

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APPENDIX A--HYDROLOGY AND PHYSIOGRAPHY OF LIMESTONE TERRANES

A. C. Swinnerton

On April 28, 1947, a symposium was held as part of the Annual Meeting of the Section of Hydrology, American Geophysical Union, on the subject Ground-water hydrology of limestone terranes. The session was reported in the minutes of the Annual Meeting [Trans. Amer. Geophys. Union, v. 28, p. 511, 1947]. At least three of these papers have appeared.

HAMILTON [1948] emphasized that the control of solutional activity is by joints and bedding planes and noted the greater extent to which solution has progressed in the valleys than in the interstream areas. MONEYMAKER [1948] states that there is extensive solution in the area, extending "hundreds of feet below the present water table" and controlled more by geologic structure than by the purity (sic) of the rock. He concludes that the solutional activity has been in progress for a very long time.

Extension of previous work by the U. S. Geological Survey along the Balcones fault zone into Comal County, Texas, was reported by GEORGE [1948]. Evidence was found to show the extent of initial development of solution at the disconformable contact between the Edwards limestone and the overlying Georgetown limestone. Subsequent development and present movement of water are controlled largely by structural features. Hence a part of the water that issues at Comal Springs has moved from the confined reservoir in the San Antonio area to the unconfined area in Comal County where the movement is roughly parallel to major faults. The water table is not yet adjusted to the streams. Comal Springs, largest of the springs in the Balcones zone, has an average discharge of 323 cfs, which is 75 per cent of the maximum discharge of record. Also indicating the extent of the reservoir are the lack of turbidity and the constant temperature of the water.

Other work which has been reported directly to the writer includes the following items:

A. S. Furcron, reporting investigations sponsored jointly by the U. S. Geological Survey and the Georgia Geological Survey in Mitchell and Baker Counties, Georgia, states that the study has special geomorphic interest because a contrasting degree of solution divides the area into two distinct Coastal Plain subdivisions; the Dougherty plain, where solution and slumping have been intense, and the Tipton upland, where solution has been less active, although sinks are common in both areas.

BERDAN [1948] investigated, as part of a cooperative program of the U. S. Geological Survey and the New York State Water Power and Control Commission, the cave systems and hydrology of the carbonate rocks in Schoharie County, New York.

During 1945 several flow and head traverses were made in a 2,130-foot well penetrating the Eocene limestones at Fernandina, Florida. According to H. H. Cooper of the U. S. Geological Survey, the results indicate that the withdrawal of 33 million gallons per day from the formation between depths of 550 and 1050 ft, lowering the head in that interval by 50 ft has had little or no effect on the head in the formations below 1050 ft. Apparently the limestone is stratified in such a way that percolation of water across bedding planes is prevented or retarded. This information is significant in relation to the possibility of salt-water contamination of the artesian waters in northeastern Florida. As long as the formations below the bottoms of producing wells contain fresh water under artesian head, the danger of salt-water contamination may be considered remote. The flow traverses indicate that the limestones below 1050 ft will yield at least as much water as those above.

In a paper entitled Ground-water aquifers of northern Illinois, presented at the 1946 meeting of the Geological Society of America, BAYS and STORM [1946] discussed the water-bearing characteristics of the Silurian dolomite, differentiating between the reef structures and the normal bedded dolomites with regard to the storage and movement of ground water. The importance for ground-water production of the pre-St. Peter cavern system of the Trempealeau dolomite was indicated.

The continuing service work of the Illinois Geological Survey includes the preparation of routine reports on ground-water possibilities, many of which deal with limestone and dolomite aquifers. The Survey is systematically collecting data on the chemical treatment of water wells in limestones and dolomites, the electrical behavior of such rocks as shown by electric logging, and other physical properties of limestones and dolomites as indicated by various geophysical measurements.

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APPENDIX B--A NOTE ON THE RELATION BETWEEN CONSUMPTIVE USE OF WATER AND FREE-WATER ACCRETION BELOW THE ROOT ZONE

G. W. Musgrave

The movement of surface water to ground-water levels is conditioned upon at least four things: (1) the occurrence of water upon the land surface; (2) permeability at the surface great enough to permit entry into the soil of appreciable quantities of water; (3) the amount of consumptive use of water by plants; (4) permeability of the profile below the root zone so that downward rather than lateral movement of water occurs.

Among these several conditions none is more susceptible of misunderstanding than (3), because very little is known at the present time about either the magnitude of consumptive use of water by various kinds of plants occurring in different climates and upon different kinds of soils, or its relation to amount of infiltration and downward movement of free water.

(Since the above was written, opportunity has been presented for conferring with H. L. Penman, whose method of computing evapotranspiration, using as a prime factor variations of solar energy, has been very effectively presented in a paper entitled, Natural evaporation from open water, bare soil, and grass [Proc. R. Soc., A, v. 193, pp. 120-145, 1948]. Also, since the above statement was made, the paper by Marie Sanderson entitled, An experiment to measure potential evapotranspiration has come to my attention [Canadian J. Res., Section C, Bot. Sci., v. 26, no. 4, pp. 445-454, August 1948]. Both of these papers indicate that appreciable progress actually is being made upon this very difficult subject of evapotranspiration.)

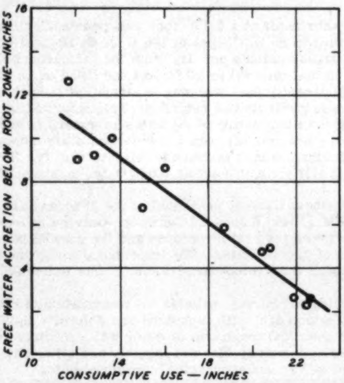

Fig. 1--Relation between consumptive use of water and free water accretion below the root zone

The fact that the amount of water moving to depths below the root zone is conditioned at least in part upon the amount of evapotranspiration is well shown by a preliminary study that attempts to measure rainfall, surface runoff, infiltration, accretion of water in the root zone, and accretion of water in depths below the root zone. The work was done on 12 small watersheds that provided four different soil-vegetal cover complexes in triplicate. The four complexes consisted of bluegrass and corn, each grown on a highly permeable soil and on a less permeable soil.

Although data for only two years are included in the study, it was found that a large and significant correlation (-0.93) existed between the amount of evapotranspiration and the amount of accretion of free water at depths below the root zone. The data for one of the years, derived by one of the methods employed in the study, are plotted in Figure 1. The computed regression is $E = 19.319 - 0.7314X$. Essentially similar data were obtained by an entirely independent method of measurement. More details of the work are being published elsewhere under the authorship of H. N. Holtan and G. W. Musgrave.

It is to be emphasized that the results are regarded at present as being applicable only to the conditions of this brief experiment and that the quantities of water involved would in all likelihood differ for other climates, soils, and vegetation. Nevertheless, it is logical to believe that the principle involving a definite relationship between amount of consumptive use and amount of water added to depths below the root zone has a general application.

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DISCUSSION OF
"TRENDS IN RUNOFF IN THE PACIFIC NORTHWEST"
by C. C. McDONALD and W. B. LANGBEIN

[Trans., v. 29, pp. 387-397, 1948]

H. W. Anderson (United States Forest Service, Berkeley 1, California)--The annual runoff of the Columbia River has been diminishing for the last 50 years. Various contributing factors have been suggested, including a corresponding downward trend in precipitation, the wasting of ice fields, higher mean temperatures, a progressive increase in depletion by irrigation, and the effects of other works of man. McDonald and Langbein have made a study of the trend of precipitation and of the relation of annual flow to combinations of water-year precipitation totals.

An index of mean areal precipitation was obtained by using the average precipitation for three areal groups and weighting these groups by weights obtained from correlating their precipitation with runoff. This seems like a good method; however, it should be pointed out that although a single figure is thus obtained, a loss of not one but three degrees of freedom should be assigned to it in subsequent analyses. This apparently was not done.

In studying the relation of annual runoff to water-year precipitation totals the authors combined the precipitation of the year of runoff with that of previous years, depleting the effectiveness of the antecedent years by means of a die-away or recession function. The choice of recession ratios was made by testing the simple correlations between runoff and the value of effective precipitation obtained for nine different recession ratios; then choosing two on the basis of highest correlations. The smaller of the two ratios yielded a variable which represented the short-time precipitation effects and the larger was said to represent the long-time effects.

An alternative expression of short-time precipitation effects on runoff is here given, some advantages of its use are outlined, and the authors' long-time effect is questioned. So that comparisons could be made, the same period of record and data were used.

First, a test of the short-time precipitation effects was made by testing the function $R = f(P_0, P_1, P_2)$, where these variables have the same meaning and units as given by McDonald and Langbein, that is, R is the water-year runoff of the Columbia River at The Dalles, Oregon (in 10^8 ac ft), P_0 is the inches of precipitation for the corresponding year, P_1 is the inches of precipitation for the first year prior, and P_2 is the inches of precipitation for the second year prior.

From this test is found that the second year prior precipitation is not significant (the value of t for this variable from the t-test is only 0.17, whereas a value of about two is required for significance at the five per cent level). If the variable P_2 is dropped and the function $R = f(P_0, P_1)$ tested, t values of five and two, respectively, are obtained for P_0 and P_1. The equation is $R = 0.088\ P_0 + 0.033\ P_1 - 0.73$, the multiple correlation coefficient being 0.706, and the standard error of estimate being 15 per cent of the mean runoff. Thus, we see that by using only two years of precipitation a slightly better correlation coefficient is obtained than the 0.690 coefficient obtained for the authors for their short-time depletion variable $P_{0.2}$.

The advantages seem to be: (1) A slightly better and far simpler expression of short-time precipitation effect is obtained. (2) It is possible to make estimates of runoff for at least a 70-year period, that is, for the whole period of precipitation record less one year. (3) The procedure of testing a large number of variables and choosing those which give the highest correlation is avoided. As Mordecai Ezekiel points out [Methods of correlation analysis, 2nd ed., p. 324], such a procedure is almost sure to yield a higher correlation coefficient than actually exists for those variables in the universe being studied.

The non-significance of the P_2 variable, the precipitation of the second year prior to the runoff, does not, of course, prove there is no long-time effect, but it suggests that any expression of such an effect be carefully scrutinized. It is known that although there has been a decline in both precipitation and runoff during the study interval, other factors have changed in a manner to produce the same effect or augment any such effect on runoff: irrigation use has increased, temperature has increased, surface storage has increased, and so on. Thus, if care is not taken an expression of long-time precipitation effect may be due in part or wholly to variables confounded with it. There is a very close correspondence between the authors' variable $P_{0.95}$ and time as expressed by the water-year (compare columns 1 and 10 of the authors' Table 2).

It is possible to test if the authors' long-time precipitation variable, $P_{0.95}$, has any effect on runoff other than that confounded with time. Using P_0 and P_1 as expressions of short-time precipitation effects, and Y (years since 1916) as the variable representing time effects, the function $R = f(P_0, P_1, Y, P_{0.95})$ is tested. The t's for Y and $P_{0.95}$ are respectively -1.35 and -0.09. It would seem that the test shows that no unconfounded long-time precipitation effect has been demonstrated.

Dropping the variable with the least t, $P_{0.95}$, an expression of the effect of time on runoff is obtained, after allowing for the principal precipitation causes of runoff, P_0 and P_1. The equation is $R = 0.084\ P_0 + 0.027\ P_1 - 0.0088\ Y - 0.44$. Y is significant, and the multiple correlation coefficient is 0.760 which is slightly better than the 0.734 obtained by the authors using their expressions of short-time and long-time precipitation effects. From the equation it may be seen that independently of the short-time precipitation the annual runoff has been decreasing at an average rate of 880,000 ac ft per year. The need for studying the actual variables inherent in this time effect is apparent.

The authors have stated that precipitation is the main factor in the hydrologic cycle and therefore deserves examination first. It seems probable that the independent effect of any one runoff cause can only be determined when all of the major causes are either studied with it or are known to be uncorrelated with it. The authors have also stated that the effect of temperature can not be determined because precipitation and temperature are strongly associated. It would seem that to the degree that this association exists, there is no need for getting the effect of temperature, but only that effect of temperature which is independent of its association with precipitation need be determined. The problem is largely one of setting up expressive variables. In fact, nearly all the factual problems of the world may turn out to be problems of correlation, and the solutions await setting up the proper expressions of the variables involved as has been stated by Edwin Arthur Burtt in his book, Right Thinking [p. 499].

The authors have pointed out the importance of obtaining long-time records of runoff, either from actual measurements or by correlation with long-time precipitation records. It might well be emphasized that to the extent that permanent changes in conditions have occurred since past runoff measurements were made, those records must be adjusted to what they would have been under present conditions. To do this, quantitative evaluation of the independent effects of all important causes of variation in runoff must be made. However, another purpose is also served, in that the causes once determined may suggest improved water management practices. As the authors state, the problem is a challenging one. McDonald and Langbein have chosen an appropriate tool in multiple regression analysis, and they have made a worthwhile start toward a solution of the problem.

Harold W. Sexton (Bend, Oregon)--This paper is a valuable contribution to the complex problem of forecasting the runoff in the Columbia River Basin, which forecasting is of vital concern to power, irrigation, and flood-control interests.

The method of Thiessen weights was used as an aid in arriving at values for average annual precipitation. The Thiessen method gives best results where the terrain has some uniformity, or in other words, uniform slopes and exposures. For terrain as irregular as the Columbia River Basin, the use of isohyetal patterns in lieu of the Thiessen method for the determining of average annual precipitation values would be preferable. It is realized that for a large basin such as that of the Columbia River above The Dalles (237,000 sq mi) estimating accurate isohyets would require extensive field work plus contributions by those familiar with each individual area.

The paper states that a downward trend from the beginning of the record to about 1935 is apparent, with recovery since then. This statement was made in connection with Figure 4, which shows annual precipitation, 1916-1944, for the basin as developed by the authors with the aid of Thiessen weights. It is further stated, "Flow of the Columbia River at The Dalles has not yet exhibited such recovery. This anomaly may be attributed to a time lag of considerable magnitude between precipitation and a component of the runoff."

An extreme example of the carry-over or lag between precipitation and runoff, according to the paper, is the Metolius River in Oregon. In 1943, the Metolius and adjoining basins experienced copious snowfall with depths of water in storage well above average. In fact, most snow courses in the area had a greater depth of water recorded in storage as of the first of April, 1943, than had ever previously been recorded. Since, according to the paper, precipitation has shown recovery since 1935 and for the nine-year period included in the paper after 1935, the Columbia River has not exhibited such recovery, it would then appear that the extreme example of lag in runoff, the Metolius River, would not peak until the following year or so after this winter of copious precipitation and the annual flow of the river would not taper off rapidly because of the implied lag between recharge of the extensive underground water supply and the resulting discharge. This was not the case, however.

The Metolius River's mean annual discharge went from well below the mean (1922-1945) in 1942, to well above the mean (1922-1945) in 1943, and then returned to below the mean in 1944. Both the increase in discharge between 1942 and 1943 and the corresponding decrease in annual discharge between 1943 and 1944, water years, exceed all other year to year increases and decreases for the period of record.

It is doubtful the Metolius River exhibits any lag sufficient, even if augmented by many similar streams, to account for the Columbia's failure to respond to the recovery in precipitation. First magnitude springs just to the south of the Metolius basin at the headwaters of the main Deschutes River apparently exhibit a lag of not more than three or four years. For example, the flow of Davis Creek, which is made up of several large springs which in aggregate have a mean annual discharge in excess of 200 cfs in the wetter years, for the seven years of usable record seems to correlate to winter precipitation in the ratio of one-half the first year, three-eighths the second year, and one-eighth the third year.

It is interesting to note that the authors mention the continued recession of the Nisqually Glacier on Mt. Rainier in Washington. Perhaps any recovery in precipitation there has been for the period covered by the paper has been sufficient only to maintain the flow of the Columbia at its low level. Seepage and evaporation losses from large reservoirs completed since the middle 30's conceivably exerted a minor influence on the failure of the Columbia River's discharge to recover.

From a hydrologic viewpoint the Metolius River is an interesting stream. The topographical drainage area was given as 325 sq mi above the Grandview gage with an average annual runoff, 1922-1945, of 58.50 inches based on this area. This topographic drainage area is all in the precipitation shadow of the high Cascades and approximately 50 per cent of the area is below the 4000-foot contour. Probable one-third of the area below the 4000-foot contour receives hardly enough precipitation to supply the normal evapotranspiration requirements correspondingly increasing the depth of runoff of the contributing area.

From what precipitation and snow course records there are for the area in which the Metolius Basin is located, it is doubtful that there is sufficient precipitation on the topographic Metolius River basin to supply the depth of runoff from the contributing area. The writer is of the opinion that an appreciable portion of the discharge of the Metolius River comes from outside the topographic basin. Fissures, and the terrain prior to the forming of the high Cascades, could be affording water from the west, and especially from the south, a means of reaching the Metolius River from outside the topographic basin.

C. C. McDonald and W. B. Langbein (Authors' closure)--The study of trends in runoff of the streams of the country will increasingly engage the attention of hydrologists as records grow in length. Studies will be made to ascribe reasons for the variations in flow to one or many causes. Analyses of changes where time is of a factor are common in hydrology and perhaps most difficult to resolve. The theory of sampling presumes that the climatologic and the chronology in hydrologic observations are samples from an infinite universe of events from which the sample is drawn at random. It is also assumed that any sample will have the same characteristics as any other if drawn under exactly the same conditions. However, when any phenomenon is sampled at successive intervals of time, the "universe" can never be precisely the same. Can we be sure that the rainfall-runoff relation is not changing? To the extent that progressive changes follow a steady rate of progression, it is sometimes possible to allow for them by shifts in the correlations but the situation may be complicated by associated trends in the climatological data. Our sampling of the independent variables may not be complete; that is, precipitation, temperature, and time may be interrelated in a way that severely restricts our conclusions. Combinations represented in the record may be entirely dissimilar to those that may have occurred prior to the record or to those that may occur in the future. Although repetitions of special combinations of precipitation and temperature may reoccur, time factor will never retrogress. According to EZEKIEL [1941] the problem is one of the greatest unsolved questions in the whole field of modern statistics. It is one where the widest possible range of judgments may be found among experts who should desirably agree on the answer.

The reviewers have touched upon some of these difficulties. Anderson criticizes the authors for selecting the proper coefficients to be applied to the precipitation data on a basis of the best fit, and then he devotes the major part of his discussion to the very same process, that is, of introducing, testing, accepting or rejecting variables solely on the basis of their correlation. As a matter of fact the procedure used by the authors in selecting values of precipitation by the method of rank to use in the study does not fall in the class that Anderson criticizes but uses. The authors' procedure is a "cut and try" process, used only for its simplicity. For example, one might fit a straight line to a set of data by "cut and try" instead of the formal least squares solution. A formal procedure for the problem encountered by the authors is described by FISHER [1924] and would have given the best fit directly, but with a much greater expenditure of time.

As a matter of fact, the authors would prefer entirely setting up equations based on physical, a priori procedure only, letting results fall as they will. For that reason the formula introduced by JACOB [1943, 1944] was used. The problem was only to find the best fit to that equation. Whether one or three degrees of freedom is lost, seems a minor point with nearly thirty data with which to work.

Anderson confirms the authors' observations that long-term precipitation and temperature are each highly correlated with time. There may therefore be a limit to the power of resolution through correlation analysis because of the high inter-association of these and possibly other variables. What is needed are observations of factors that are completely independent.

The authors believe that ground water deserves consideration in the analyses and eventually it is hoped that deduction as to its influence can be gathered from direct observation of water levels. In the mean time we are faced with an observed decrement in runoff that seems to exceed that explainable by year to year precipitation.

Sexton's comments on lag of Metolius River are adequately answered by PIPER [1948] and require no further consideration in this discussion. The authors in placing the word topographic in quotes intended to suggest that the surface watershed does not necessarily measure the source of the flow of that river.

The discussers show that they too, like the authors, have become aware of the difficulties of resolving runoff into separate causes.

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DISCUSSION OF
"RUNOFF FROM RAIN AND SNOW" by ARTHUR M. PIPER
[Trans., v. 29, pp. 511-520, 1948]

Harold W. Sexton (Bend, Oregon)--As a basis to study the discharge characteristics of the Metolius River the John Day River was used. The Deschutes Basin of which the Metolius drainage area is a part was compared to the John Day Basin. There are several factors which must be considered when comparing the two basins. Perhaps the most important point which was not stressed is the fact that although about three-fourths of the flow of the Deschutes River rises in the westernmost part of the Deschutes Basin, which part was more or less exempted by Piper in his discussion of general runoff characteristics, it is less than half of the Deschutes Watershed.

More emphasis could have been placed on this westernmost part or east flank of the Cascade Range in regard to annual precipitation. After subtracting a reasonable depth of water for annual replenishment of soil water requirements, the precipitation on the westernmost part of the Deschutes Basin exceeds by several times the precipitation on any general area of the John Day Basin.

No evidence was presented to show whether the storms that deposit copious precipitation on the east flank of the Cascade Range distribute water on the John Day Basin in a uniform proportion. In traveling from the westernmost edge of the Deschutes or Metolius River drainage areas towards the John Day Basin or eastward, the departure from a humid area to a semi-arid or even arid area is rapid.

It is the opinion of the writer that there is a distinct possibility the precipitation pattern for the John Day River Basin is not uniformly proportionate to that of the Metolius River drainage area in individual years and perhaps in a succession of years. The inclusion of supporting meteorological data in the paper would have afforded one a better opportunity to evaluate properly the comparison of the runoff of the Metolius and John Day Rivers.

The statement is made in the paper of a striking example of five-year lag in a certain part of the Pacific Northwest . This statement by the author is misleading, as it was inferred that this statement basically referred to a lag of five years between precipitation and runoff in the case of the Metolius drainage area. Actually, there was demonstrated only a lag between two streams. Final analysis, as far as this particular approach to the precipitation-runoff relationship of the Metolius is concerned, must wait until suitable information on the variations in the weather pattern, such as they may be, between the two areas in question is made or becomes available.

It is the opinion of A. E. Perry, Deschutes County Watermaster, that other springs in the upper Deschutes River Basin which are similar to those discharging into and making up the main flow of the Metolius River do not exhibit a lag of the order of five years. These other springs are located south of the Metolius topographic drainage area and are of first and second magnitude. From the evidence gathered to date, above-normal precipitation seems to be reflected in these springs' discharge, principally within two years, with a much-reduced effect in the subsequent years. However, each individual spring including the Metolius River, has its own peculiarities.

It is agreed that the runoff of the Metolius River exceeds the precipitation on the river's topographic drainage area after the deduction of a reasonable depth of water for natural evapotranspiration. As a matter of information, the possibility of the appreciable distortion of the runoff characteristics of the Metolius River by irrigation infiltration around Bend is remote.

Piper has made some excellent suggestions in regard to facilities for improved reliability in forecasting from snow surveys.

Arthur M. Piper (U. S. Geological Survey, Portland, Oregon, Author's closure)--The tenor of the discussion by Sexton is a regret, which the writer shares, that the paper did not fully treat the hydrology of the area drained by the John Day and Deschutes Rivers. However, such was not the intent of the paper; indeed, factual information now available is quite inadequate for a full treatment. Sexton raises several points which are pertinent to the hydrology of the area, as such; these cannot be resolved rigorously until the factual record becomes much more comprehensive.

Two expressions of caution seem desirable: (1) Sexton cites "opinion" that for certain large springs analogous to those in the Metolius River basin, fluctuations of discharge do not lag much more than two years after fluctuations of precipitation. However, with respect to the springs of the Metolius basin, for which the writer graphically demonstrated a lag of at least five years, prior opinion commonly held that fluctuations of discharge were nominal or negligible. (2) Sexton would admit only a remote possibility that infiltration from irrigation near Bend may have distorted the natural runoff characteristics of the Metolius River appreciably. In the judgment of the writer it is entirely possible that the ground-water body which sustains the springs of the Metolius basin may be recharged in part by the infiltration of irrigation water. However, the volume of ground water intervening between the irrigated lands and the springs must be very large, relatively; at least in part, the rocks containing that water are known to be extremely porous. Under such conditions, fluctuations in amount of infiltration would be damped within a relatively short distance; consequently, the effect of infiltration on spring discharge would be extremely difficult to demonstrate even though it might be appreciable.

The discussion by Peterson, published with the paper, brings out the intensely practical utility of dependable runoff forecasts in efficient operation of an extensive hydro-electric generating system through the low-water months. He poses a challenge: "What are we waiting for?" in developing such forecasts according to principles suggested in the initial paper? The response is one of self-criticism: Why and wherein has the hydrologist in public service so failed to "sell" the application of his skills that chronically his facilities are so small in proportion to the opportunities for constructive service?

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REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

JOHNSTONE, DON, and CROSS, WILLIAM P., Elements of applied hydrology, Ronald Press Co., New York, x + 276 pp., 1949.

This book is not simply another treatise on hydrology. It brings to the reader the important researches and findings made and tested during the past fifteen or twenty years.

The book is primarily designed as a student's text book for use in engineering schools and agricultural colleges. The practicing engineer, however, will find it a useful guide and correlator in modern hydrologic applications.

The old coefficients of runoff, in use for nearly one hundred years, are gone. If it is desired to save a good old formula, like the rational method, for example, then this book will show how to derive a coefficient c without guess work or inate perspicuity.

The book is divided into ten chapters. Chapters 2 and 3 on precipitation and runoff include text and illustrations of procedure used in collecting the data. Reference is made to location of official records and data. Chapter 4 presents the relation of runoff to rainfall. It points out the futility of runoff percentage and is a prelude to Chapter 5, on the role of the land, which includes infiltration, transpiration, and ground-water storage.

The unitgraph (unit hydrograph) is clearly described in Chapter 6. It gives procedure for derivation and practical applications. A chapter on flood routing follows. This is primarily in the domain of hydraulics. However, it is pertinent and useful in the hydrology of hydrographs.

Chapter 8, on infiltration and analysis of the hydrograph, is the most important chapter in the book. It is the essential key in modern hydrology. The text and clear diagrams make the reader understand all of Nature's phenomena from which we derive the rates of infiltration, in inches per hour, on different areas, soil, vegetal cover, and topography. Derivation of f_c (ultimate constant rate of infiltration) gives, in the reviewer's opinion, an essential in the infiltration method.

Chapter 9, on the hydrograph as a function of the drainage area, is a corollary to the unit hydrograph. It covers an important phase of applied hydrology including the synthetic unit hydrograph of Snyder and others. It indicates the selection of a unit hydrograph, applicable to an unmeasured basin, from adjacent and similar measured areas. Chapter 10 is a good short text on statistical analysis. The book has a closure, with suggestions to teachers, on problems, questions, and special assignments.

The authors of this book admit the omission of important details of technical procedure, required by the practicing engineer, but precluded by size limits of a text book. They have made up for this omission, in part, by the bibliography and reference notes, in each chapter, relating to the text.

A book, like this one, has been made possible through the coordinated and critical work of the membership of the Section of Hydrology, American Geophysical Union. This includes the hydrologic staffs of the U. S. Departments of Agriculture and the Interior, the U. S. Weather Bureau, the Army Corps of Engineers, and many of the state agencies dealing with waterways and natural resources.

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NOTES AND PERSONALIA

NOTES

Corrigenda--The following corrections are noted in the Transactions:

Vol. 30, June 1949, in the paper by Putnam, Munk, and Traylor, p. 337, the paragraph entitled, "Beach Observations," was omitted in the second line.

In the same issue, in the paper by W. B. Zerbe, p. 358, the equation at the top of the page should read as follows:

$$\begin{aligned} F_a/g &= 9(U \sin 2Y \cos a \, \Sigma fC_0 \cos E_0)/8 \\ &+ 3[UP_1 \, \Sigma fC_1 \cos (E_1 - X_1)]/2 \\ &+ 3[UP_2 \, \Sigma fC_2 \cos (E_2 - X_2)]/2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (1) \end{aligned}$$

On page 359, in the fourth full paragraph on the page, in the sentence beginning, "The general downward--," the word "which" should be deleted. On pages 361 and 362, the figures should be interchanged, the title on 361 belonging with the figure on page 362. On page 366 in the paragraph below the figure in the ninth line, the 1/2 should be deleted so that it reads, "the XI-hour or the XI 1/2-hour line.

In the same issue, in the Minutes of the Section of Meteorology, p. 469, the title of paper (14) by Joachim Kuettner should be "The electrical and meteorological conditions in the bases of thunderclouds."

Conference on sea ice in Hudson Bay held in Canada--A conference on winter sea ice in Hudson Bay was held by the Section Meteorology and Hydrology of the Associate Committee on Geodesy and Geophysics of the National Research Council of Canada in Ottawa on April 12, 1949. F. K. Hare and M. R. Montgomery brought out that, contrary to the general traditional thought that there is open water in the Hudson Bay all winter, none was found in the winters of 1947-1948, and 1948-1949, for a period of about five months, and that the gulf of warm air that normally occurs over open water disappeared by the end of December.

F. E. Burbidge of the Meteorological Service of Canada reported modification of continental polar air masses passing over Hudson Bay during November and early December, but later that the Bay appeared to act as a continental surface.

Publication of two German volumes on geophysics--Volumes 17 and 18 of Naturforschung und Medizin in Deutschland, 1939-1946, relating to various aspects of geophysics, have recently been published by Dieterich'sche Verlagsbuchhandlung in Wiesbaden. The editor is Julius Bartels of the University of Göttingen. The papers published are cited in the bibliography of this issue.

Publication on ocean surface waves--This monograph, edited by Bernhard Haurwitz, presents the results of the Conference on Ocean Surface Waves held by the Section on Oceanography and Meteorology of the New York Academy of Sciences on March 18 and 19, 1948. It has been published as Volume 51, Article 3, of the Annals of the New York Academy of Sciences, pages 343-572, May 1949. The issue includes 15 papers by specialists on all phases of ocean-wave research and technology, together with some amplifying discussion.

Formal establishment of the Geophysical Institute of the University of Alaska--The interim organization known as the Geophysical Observatory of the University of Alaska is soon to be superseded by the Geophysical Institute, established by Public Law 580 of the 79th Congress. The construction of the buildings authorized is nearly complete, and a staff of 33 are now engaged on the research program of the Institute.

Fall Meeting of U. S. National Committee of URSI and the IRE--A joint meeting of the USA National Committee of the URSI and the recently organized Professional Group on Antennas and Propogation of the IRE will be held in Washington, D. C., October 31 to November 2, 1949 in the auditorium of the National Academy of Sciences. Details may be secured through Newbern Smith, Secretary-Treasurer of URSI, National Bureau of Standards, Washington 25, D. C.

Fourth Hydraulics Conference at University of Iowa--The Fourth Hydraulics Conference of the Iowa Institute of Hydraulic Research was held at the University of Iowa in Iowa City, Iowa, June 12-15, 1949. Fourteen papers were presented, thirteen bearing on the major active field of hydraulic engineering, with a general address on present-day trends in hydraulic engineering by A. L. Alin. The proceedings will be published, and can be secured through the University of Iowa.

New map showing status of topographic mapping in the United States--The United States Geological Survey has issued two new maps showing the current status of topographic mapping in the United States, its territories and possessions. The work done to standard scale is shown in the first of these two, designated as Map A, while reconnaissance mapping is shown on Map B. Copies may be secured through the Map Information Office of the U. S. Geological Survey, Washington 25, D. C.

Seismic work on Alaska glaciers--The Stanford Research Institute is cooperating with the American Geographical Society in making seismic measurements on glaciers around Juneau, Alaska. This is a part of a long-time study being conducted on ice conditions in that area.

Civil Service positions open for geophysicist in exploration work--The Civil Service Commission has announced examinations for vacancies in geophysical exploration work, grades P-2 to P-5. Interested persons should apply at any Civil Service office for Announcement No. 177 and the necessary forms.

Geophysical seminars at the Cambridge Field Station of the United States Air Forces--A series of seminars was held during the summer months of 1949 by the Geophysical Research Directorate of the Cambridge Field Station, AMC, USAF in the Watertown, Massachusetts arsenal on a broad field of subjects, bearing chiefly on atmospheric and surface phenomena. The ones on August 26 and August 30 will be conducted by Joseph Kaplan and will relate to the spectra of the night sky and the upper atmosphere.

Symposium bearing on geophysics at Woods Hole--A symposium on Applications of Auto Correlation Analysis to Physical Problems was held at Woods Hole Oceanographic Institution, June 13 and 14, 1949. A wide range of subjects, including communication and fire control problems, was covered but papers bearing on ocean waves, weather problems, and other aspects of geophysics were also included.

Aeronautical science meeting in Elmira, New York--The Second Joint Meeting of the Institute of the Aeronautical Sciences and the Soaring Society of America was held in Elmira, New York on July 8, 1949. Five papers were presented at the afternoon session bearing on aerodynamics, and three at the evening session bearing on meteorology.

Revision and republication of Physics of the Earth Series, Volume VII--Internal constitution of the Earth which is Volume VII of the above series is now in the process of revision and will probably be ready for the printer about the end of the year. The new edition should be available about January 1, 1951.

PERSONALIA

Charles E. Bunnell, President of the University of Alaska for the last 27 years, became President Emeritus of the University as of July 1, 1949.

John A. Fleming, Honorary President of the AGU and Past-Director of the Department of Terrestial Magnetism of the Carnegie Institution of Washington, was honored June 3, 1949 on the occasion of the presentation of an oil painting of himself by the staff of the Department of Terrestrial Magnetism to the Carnegie Institution of Washington. With the approval of the Administration Officers of the Carnegie Institution, this painting will be retained in the library of the Department of Terrestrial Magnetism.

Weikko Heiskanen, Director of the Isostatic Institute in Helsinki, has been designated by the President of Finland, as the Director of the Finnish Geodetic Institute, succeeding Ilmari Bonsdorff who had been director for 30 years. He will continue as the Director of the Isostatic Institute.

Stuart L. Seaton, Director of the Geophysical Observatory of the University of Alaska, has been awarded an honorary degree of Doctor of Science by the University of Alaska.

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MINUTES OF EXECUTIVE COMMITTEE MEETING, AMERICAN GEOPHYSICAL UNION

Meeting of April 23, 1949

The meeting was called to order at 09^h00^m in the Reading Room in the National Academy of Sciences - National Research Council Building, 2101 Constitution Avenue, Washington, D. C. by President Walter H. Bucher.

Present--Thirty-four persons were present, namely: L. H. Adams, Robert Balk, K. Hilding Beij, Merrill Bernard, W. H. Bucher, Wilbur S. Burbank, Horace R. Byers, Ernst Cloos, Frank L. Culley, H. N. Eaton, Jno. A. Fleming, Richard H. Fleming, Wm. F. Foshag, R. C. Gibbs, H. D. Harradon, H. W. Hemple, Benjamin Holzman, M. King Hubbert, Woodrow C. Jacobs, H. Freeborn Johnston, J. W. Joyce, David G. Knapp, W. D. Lambert, Ray K. Linsley, Jr., J. P. Marble, Geo. F. McEwen, A. G. McNish, Frank Neumann, F. W. Reichelderfer, Florence Robertson, Irwin Roman, James B. Small, Waldo E. Smith, and Merle A. Tuve. The following were excused because of absence from the city or for other reasons: Fred Anderegg, J. Bjerknes, J. E. Church, Ralph E. Cleland, R. E. Fuller, H. H. Hess, C. O'D. Iselin, Lorenz G. Straub, V. C. Stechschulte, W. D. Sutcliffe, and Howel Williams.

Approval of Minutes--The minutes of the meeting on December 3, 1948 as published in the February 1949 issue of the Transactions, pages 152 to 158, were approved.

General Secretary's Report

Executive Committee--The membership of the Executive Committee has not changed since the meeting on December 3, 1948. Harald U. Sverdrup has resigned as Vice-President but retains membership on this Committee by virtue of his past presidency of the Section of Oceanography and the fact that he is an American officer of the International Union of Geodesy and Geophysics. F. W. Reichelderfer was designated by the Executive Commitete as Vice-President but was already a member of the Executive Committee by virtue of his past presidency of the Section of Meteorology.

Personnel--Mrs. Marguerite H. Salm resigned as Clerk-Typist effective as of March 31, 1949, and Miss Beverly Beckett has been appointed in her place.

Financial Report--A detailed financial statement will be prepared as of June 30, 1949, and will be referred to the Committee on Audit. As of March 31, 1949 our balance was $18,421.65 including investments at cost of $2,768. This is substantially lower than the balance of $22,705.58 on March 31, 1948 and reflects the termination of grants and the increase in almost all costs, showing the need for the increase in dues recently approved by the membership. The recommendations with regard to investments in a building and loan association at the December 3 meeting have been carried out, and and a deposit of $400 has been made at an interest rate which is currently three per cent.

Membership--The Membership Committee has been reorganized during the last year, and the results of their efforts are now beginning to be evident. Despite the fact that as usual we had about two per cent resignations, our membership has continued to grow slowly so that the membership as of April 20, 1949 is 4,449, a net increase of 65 since the last report. The following is a summary.

Members, November 26, 1948	4,384	
New members	150	
Reactivated	5	4,539
Resignations	69	
Deceased	15	
Inactive	5	
Dropped for non-payment of dues	1	90
Membership, April 20, 1949		4,449

Fifteen deaths have been reported since November 26, 1948, namely, Chas. S. Slichter, October 5, 1946; Alexander L. de Toit, February 25, 1948; Rollin T. Chamberlin, March 6, 1948; Gayle

Scott, May 1, 1948; Henry R. Stevens, May 14, 1948, Robert W. Clark, June 5, 1948; Daniel W. Mead, October 13, 1948; Americo R. Peracca, October 24, 1948; Henry G. Wrocklage, December 10, 1948; Joseph W. Thomas, Jr., January 9, 1949; Francis P. Gilbert, January 17, 1949; A. Perry Banta, January 23, 1949; Henry L. Haehl, January 29, 1949; Samuel H. McCrory, February 18, 1949; and Bailey Willis, February 18, 1949.

One hundred two members are in arrears in dues for 1947 and 1948. It is recommended that those not responding favorable be dropped from membership after one more notice.

In addition 27 persons elected to membership during the active campaign of a year ago have not yet accepted. The Executive Committee has granted authority of the General Secretary to drop these after six months, and after one more notice those not responding favorably will be dropped.

Corporation Membership--In accordance with the recent ballot of the Executive Committee, Keuffel and Esser Company has been elected to Corporation Membership in the American Geophysical Union, bringing the total number to date to four.

Administration of the Union--F. W. Reichelderfer was designated Vice President in place of H. U. Sverdrup, resigned.

Arrangements have been made for the continuance of quarters in the Administration Building of the Carnegie Institution of Washington for another year (to about February 1, 1950) at which time the matter is to be reviewed again.

The ballot on the increase in dues resulted in a vote of 1,432 in favor, 499 opposed, 72 ballots rejected, a total of 2,003 ballots. Fourteen ballots were rejected because of non-identification; 26 ballots came from non-citizens of the United States; two ballots were blank; three were from new members who had paid no dues; and 30 were mailed after the closing date, March 5, 1949. Since the tally of the ballots, several more have come in. It is interesting to note that a very great majority of the late arrivals were affirmative votes. Interesting also is the fact that of the 26 non-citizen ballots cast, 22 favored the increase and only four were opposed. Considering the prior action of the Executive Committee, the dues for 1950 will be $ 7.

The Committee on Regionalization, which was created at the last meeting of the Executive Committee, has been designated with Merrill Bernard as Chairman, and Harry H. Hess, Earl Ingerson, John Putnam Marble, and G. Medina as members.

The Committee on Student Membership and Student Chapters has been designated with two members; Woodrow C. Jacobs, Chairman; and Florence Robertson.

National Research Council--The National Research Council is continuing its usual annual grant of $400 for next year.

The term of Ernst Cloos as AGU representative on the Division of Geography and Geology in the National Research Council expires June 30, 1949. By the direction of the Executive Committee at its meeting December 3, 1948, the President will designate the new appointee.

Meetings--The Twenty-Third Regional Meeting of the American Geophysical Union was held in Los Angeles, February 4 and 5, 1949. About 200 were in attendance and very good reports have been received of the meeting. Only the Sections of Hydrology and Meteorology had sessions.

The Twenty-Fourth Regional Meeting of the Union will be held in Denver next week, April 26 to 28, by the Section of Hydrology jointly with the Western Snow Conference.

An invitation was received in February to meet jointly with the Pacific Division of the American Association for the Advancement of Science in Vancouver, British Columbia, June 13 to 18, 1949. The possibilities in this regard were canvassed, and it was the concensus that it was too late to attempt to organize and arrange a program in the short time available.

Publications--We continue to publish our bimonthly Transactions in an edition of 5,200. Since our last meeting, the December and February issues have been released and distributed. The April issue has just been released from the printers and is being prepared for the mail.

The foreign exchange and subscription list is still growing so that we now finally have a feeling that our Transactions are received by most of the important libraries and geophysical institutions throughout the world.

The Editorial and Publications Committee has completed the job of indexing the first 25 years of the Transactions, and during the summer and early fall these entries will be edited and prepared for printing.

An interesting suggestion concerning publications has been made by Merle A. Tuve, Director of the Department of Terrestrial Magnetism and Electricity. As a result he has been invited to attend this meeting to present his suggestion.

American Geological Insititute--In accordance with the action by the Executive Committee on December 3, 1948, the President appointed Ernst Cloos and W. T. Thom, Jr. as directors from the American Geophysical Union on the Board of the American Geological Institute. The term of Cloos will expire November 30, 1949 and that of Thom, November 30, 1950.

UNESCO--The Second National Conference on UNESCO was held in Cleveland March 31, to April 2, 1949. Kenneth E. Caster, George H. Harding, and C.V. Youngquist were designated as representatives from the American Geophysical Union.

American Standards Association--The arrangement initiated within the Section of Hydrology with the American Standards Association to create a Committee on Permeability has been concluded, and Charles E. Jacob is the Chairman and representative from the American Geophysical Union. The Committee has been designated the Committee on Permeability Z59.

Action on the General Secretary's Report--The report was approved, including the recommendation concerning members in arrears in dues.

Reports of Standing Committees

Membership--Chairman Small reported that the Committee is actively getting into touch with prospective members, and that the rate of growth in membership is increasing.

Corporation Membership--Chairman Roman stated that he recently sent out a number of letters inviting organizations to corporation membership, that one favorable response has come in, and that others are pending.

Meetings--Chairman Marble discussed the Thirtieth Annual Meeting briefly, pointing out especially the success of the joint session meetings with the plan to develop such sessions in subsequent meetings. He reported that the dates set for the Thirty-First Annual Meeting are May 1 - 4, 1950.

Editorial and Publications --Chairman Beij raised the question concerning the size of the edition of the index for the first 25 years of the Transactions to be issued later this year. There was some discussion with the general thought that about 2,500 might be about correct. It was suggested that some helpful advice might be received from Colin Campbell, Business Manager of the Society of Exploration Geophysicists.

Budget--Chairman Eaton presented the budget for the fiscal year ending June 30, 1950 as set forth in Appendix 1. After discussion the budget was approved.

Reports of Special Committees

Regionalization--Chairman Bernard outlined the steps the Committee has taken to study this problem; namely, that the Committee had written a group of members in twenty vicinities to feel out sentiment. A few answers had been received that would be studied and the findings would be incorporated in a later report. There was some discussion which should be helpful in guiding the Committee.

Cosmic-Terrestrial Relationships--Chairman Stetson filed a report on the work of his Committee which has been published in the June 1949 issue of the Transactions, pp. 464-466. An addendum to the report is given in Appendix 2.

Study of Tsunamis--Chairman Mason filed a report on the work of his Committee which has been published in the June 1949 issue of the Transactions, page 466.

Reports of the Sections

Geodesy--President Hemple reported that Charles A. Whitten has been designated as the American representative on the Permanent Committee of the Association of Geodesy, IUGG, to succeed Walter D. Lambert. He also reported that Walter D. Lambert had received the Exceptional Service Award of the Department of Commerce at a recent ceremony.

Terrestrial Magnetism and Electricity--The question was raised concerning the American distribution of the Report on the Oslo Meeting of the Association of Terrestrial Magnetism and Electricity, IUGG. After considerable discussion, it was approved that announcements of the availability of this report, and those of other associations of IUGG be published in the Transactions, and that copies be supplied at cost including handling and mailing to those requesting them.

Hydrology--Secretary Linsley reported that the Section made awards as follows: Best Paper Award for 1948, to R. A. Work for his paper, "Snow Layer Density Changes" [Trans. v. 29, August 1948]; and the Best First Paper Award for 1948, to Gordon Chapman for his paper, "Size of Raindrops and their Striking Force at the Soil Surface in a Red Pine Plantation" [Trans. v. 29, October 1948].

Other Reports

Division of Physical Sciences, NRC--Chairman Gibbs reported on the scholarship program of NRC and the availability of funds to aid in carrying out research work.

American Geological Institute--Ernst Cloos, one of the two AGU representatives, reported the organization of the Institute, the designation of officers, and formulation of committees to initiate and carry on the work of the Institute.

New Business

Proposal of M. A. Tuve--Merle A. Tuve presented a proposal for a Journal of Geophysical Research, to take over the functions of the journal of which he is now editor. Incorporated in the suggested journal would be the more fundamental papers that normally appear in our Transactions, similar papers normally submitted for publication in his journal, and such other papers, now normally published elsewhere that might be channelized into a strong journal. Transactions would continue to be published in reduced size, and members would receive both publications for their membership fee. The new publication, published preferably by letter press rather than by off-set, would cost, he said, about $21,000 per year and would thus increase the budget of the Union substantially. There was very free discussion bringing out points on both sides of the proposition. A motion by Balk was finally approved as follows: (1) Tuve shall formulate his proposition in a written statement submitted to AGU. (2) The President of AGU shall transmit this statement to the present Editorial and Publications Committee or to a special committee appointed to advise the Editorial and Publications Committee on this matter. (3) Not later than twelve months after the adoption of this motion, the Editorial and Publications Committee or the specially appointed advisory committee is to report its findings to the Executive Committee. (4) The Executive Committee shall discuss the matter and, if it is thought necessary, shall call for a ballot from the whole membership of AGU. (The President has since appointed F. W. Reichelderfer, Chairman; L. H. Adams; H. N. Eaton; E. A. Eckhardt; and H. W. Hemple as this Committee. Any thoughts concerning this matter should be forwarded to the office of AGU. They will be transmitted to the Committee promptly.) A motion by Cloos to require that the report of the Committee be circulated among the members of the Executive Committee at least two weeks before the meeting at which it is to be acted upon was also adopted.

Adjournment--The meeting was adjourned at 12^h25^m.

K. HILDING BEIJ, General Secretary
WALDO E. SMITH, Executive Secretary

APPENDIX 1--REPORT OF THE COMMITTEE ON BUDGET FOR THE FISCAL YEAR ENDING JUNE 30, 1950

H. N. Eaton, Chairman
Jno. A. Fleming Roy W. Goranson N. C. Grover

The Committee on Budget of the American Geophysical Union has conferred with the General and Executive Secretaries of the Union regarding the budget for the fiscal year, July 1, 1949, to June 30, 1950, and proposes the following budget. Last year the form of statement was changed for the sake of clarity to separate the Operating Statement of Receipts and Expenditures from the Statement of Assets and Liabilities. This year a further change has been made, in that separate Operating Statements are being given for the Robert E. Horton Fund and the William Bowie Medal Fund, as

well as for the general funds of the Union, because of confusion that arises from combining the special funds with the general funds in a single Operating Statement.

The Committee has added one new item to the statement of estimated expenditures. The Budget Committee voted, after due consideration, to recommend to the Executive Committee that an item of $250 be included in the budget each year in order to accumulate the sum of $750 every three years for paying the expenses of travel of the Executive Secretary to the triennial meetings of the International Union of Geodesy and Geophysics.

It will be noted that the Operating Statement for the coming year is much more favorable than it has been for some time past. The increase in dues from $5 to $7 should place the Union on a sound and self-sustaining basis.

Statement of assets and liabilities as of June 30, 1949 (estimated)

Assets			
Cash reserve, general funds		$ 6,570	
Permanent fund:			
U. S. Government bonds (at cost)	$2,368		
Northwest Federal Savings and Loan	500	2,868	
Robert E. Horton Fund		1,100	
William E. Bowie Medal Fund		113	$10,651
Bills receivable			2,000
			$12,651
Liabilities			
Bills payable		$ 300	
Surplus		12,351	$12,651

Operating Statement (General Funds)

Estimated receipts		
National Research Council, grant		400
Income		
Dues, 4000 members	$28,000	
Dues, four corporation members	400	
Sales, Transactions	3,000	
Sales, reprints	1,500	32,900
Total receipts		$33,300
Estimated expenditures		
Publication of Transactions:		
Printing	$ 8,000	
Preparation	7,600	
Mailing and postage	1,100	$16,700
Reprints		1,500
Co-editors		1,500
General office expenses:		
Salaries	$10,000	
Stationery and supplies	1,200	
Postage and communications	1,200	
Equipment	400	$12,800
Expenses, meetings:		
Annual	$ 500	
Regional	300	800
Expenses, Sections		200
Expenses, Committees		600
Travel of officers		250
Travel of Executive Secretary to international meetings		250
Membership list[a]		500
Total expenditures		$35,100
Excess of expenditures over receipts (withdrawn from reserve)		$ 1,800

Operating Statement (Robert E. Horton Fund)

Estimated receipts	0	
Estimated expenditures	$1,100	
Excess of expenditures over receipts (balance as of July 1, 1949, $1,100)		$1,100

Operating Statement (William Bowie Medal Fund)

Estimated receipts	0	
Estimated expenditures	$ 20	
Excess of expenditures over receipts (balance as of July 1, 1949, $ 113)		$ 20

Statement of assets as of June 30, 1950 (estimated)

General funds, cash reserve	$4,770	
Robert E. Horton Fund	0	
William Bowie Medal Fund	93	
Permanent Fund, investments	2,868	$7,731

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[a] Half of estimated cost budgeted this year.

APPENDIX 2--ADDENDUM TO REPORT OF COMMITTEE ON COSMIC-TERRESTRIAL RELATIONSHIPS FOR THE YEAR 1948-1949

[Trans. v. 30, pp. 464-466, June 1949]

Serge A. Korff reported as follows:

Work accomplished during the year include four balloon flights carried out in Denver last summer. On these flights. we made further measurements of the neutrons associated with the cosmic radiation. We were trying out a number of different experimental arrangements for separating the several components of the neutrons, we well as trying out new systems for recording the data and for better controlling the time and altitude characteristics of the flights. We feel that we have greatly improved our instrumentation. We have a series of flights scheduled for the coming summer.

Our studies of the properties of counters have also gone forward. We made a mass-spectrographic analysis of the progressive decomposition of polyatomic quenching constituents in self-quenching counters and found this to fit with the predictions of the Korff-Present theory. We can now predict the useful lifetime of a counter with any assigned filling.

HARLAN T. STETSON, Chairman

Twenty-Fourth Regional Meeting Held in Denver

The Twenty-Fourth Regional Meeting of the American Geophysical Union, Hydrology Section, and the Seventeenth Annual Meeting of the Western Show Conference were held jointly in the Shirley-Savoy Hotel, Denver, Colorado, on April 26, 27, and 28, 1949. One hundred and twenty-five members and guests of the two organizations from the western states of Colorado, Utah, New Mexico, Arizona, Texas, Oklahoma, Nebraska, Wisconsin, North Dakota, Minnesota, Montana, Idaho, Nevada, California, Wyoming, and Oregon, and from the Canadian province of British Columbia were in attendance.

The address of welcome was delivered by Clifford H. Stone, Director, Colorado Water Conservation Board. Papers on the first day's session were devoted to economic aspects of snow, snow problems of the Colorado State Highway Department, progress in snow-melt investigations at the Fraser Experimental Forest, Cooperative Snow Investigations, anchor and frazil ice, and wind studies on shielded snow gages. The second day's session was centered about papers on summer-storm characteristics, river forecasting determination of snow-melt rates, infiltration and retention tests, hydrology of stock ponds, and tree-ring correlations. Several of the papers will be submitted for publication in the Transactions. A joint banquet on the evening of April 26, attended by all conferees and their ladies, featured addresses by Chief Justice Hilliard of the Colorado Supreme Court and J. E. Church, world-eminent authority on snow surveys.

Tours of the Colorado-Big Thompson Trans-Mountain Diversion Project, and the engineering laboratories of the Bureau of Reclamation highlighted the activities of the final day of the meeting.

C. E. Knox of the U. S. Geological Survey in Boston, Massachusetts, attended the meetings as representative of the Eastern Snow Conference. The Engineer Research and Development Laboratories of the Corps of Engineers at Fort Belvoir, Virginia, were represented by Chauncey W. Karstens and Paul A. Beigbeder.

Ralph L. Parshall, Emeritus Senior Irrigation Engineer of Colorado A. and M. College, was General Chairman of the Western Snow Conference and Herbert S. Riesbol, Assistant Chief, Hydrology Division, Branch of Project Planning, Bureau of Reclamation, was Chairman of the American Geophysical Union meeting. Bert Goodell of the U. S. Forest Service at Fort Collins was Program Chairman for Western Snow Conference, and Victor Koelzer, Bureau of Reclamation, Denver, was Program Chairman for American Geophysical Union.

H. S. RIESBOL, Chairman

REPORT OF DELEGATES OF THE AMERICAN GEOPHYSICAL UNION TO THE SECOND NATIONAL MEETING OF THE UNITED STATES COMMISSION ON UNESCO, CLEVELAND, OHIO, MARCH 31 to APRIL 2, 1949

The American Geophysical Union was represented at the Second National Meeting of the United States Commission of UNESCO by Kenneth E. Caster of the University of Cincinnati, George H. Harding of Ohio State University, and C. V. Youngquist of the Ohio Water Resources Board. The meeting was held in Cleveland, Ohio, March 31 to April 2, 1949.

The sessions of most interest to our delegates were group meetings of the Professional and Scientific Organizations. Robert M. Gates, representing the Engineers Joint Council gave the keynote address before this group. Youngquist, commenting on the high lights of this address reported the organization of a nonprofit group, Overseas Consultants, to aid countries requiring technical and scientific assistance, and that "Gates emphasized the importance of recognizing human values in assisting foreign peoples; that the structure of better living must be on their own foundation." Quoting from the Gates address, "They want opportunity to climb to a higher plane of living, but that way may be quite different from the North American or Western European way of life. . . . I need hardly add that all who take part in the curative and creative work promoted by UNESCO need not only this human understanding, but also a spirit of unselfish service."

Caster comments, "At the present point of international cooperation on the UNESCO plane, above all else the movement needs. . . . an enlightened American public behind it. . . . The most significant contribution. . . . to be made by AGU, in common with every other learned and professional organization in the country, is for the central officers. . . . to undertake some plan of information. . . . among the memberships with respect to UNESCO's aims and objectives." He comments that often professional people, who should be intellectual leaders in their communities fail in their community responsibilities. "Our responsibility seems to be personal and individual; any effect which AGU may be willing to exert to catalyze its membership to a more poignant awareness of this responsibility is not only a magnificient service to UNESCO, but an adoptional pattern of thinking of highest survival pattern."

Harding warns again of the danger of attempting to "tell those various countries how to improve their economic, technical, and moral standards". . . . and that it must be a mutual interchange of of ideas, and mutual assistance. . . . with no attempt to establish or impose "our way of doing things."

The serious concern of the membership is invited to these important matters.

American Standards Association--Fred Anderegg, AGU representative on the Committee on Photograpny Z38 of the ASA advises that the latest approved standards are as follows:

Z38.8.20-1948, American standard method for determining the melting point of the photographic layer of film, plates, and papers.

There are also 24 new American standard specifications for photographic grade chemicals. Any of these may be requested from the AGU representative, c/o Photogaraphic Services, University of Michigan, Ann Arbor, Michigan.

Transactions, American Geophysical Union Volume 30, Number 4 August 1949

ADDITIONS TO THE MEMBERSHIP OF THE AMERICAN GEOPHYSICAL UNION, JANUARY 11, 1949 TO JULY 10, 1949

Abrahamson, Mr. Sherman, 1406 48th Ave., S. E., Washington 19, D. C. (c)
Absher, Mr. L. M., 7921 Findlay St., Houston 17, Texas (abh)
Ackerman, Miss Bernice, 629 Stratford Pl., Chicago 13, Ill. (ceg)
Ackerman, Mr. Rolland F., 405 Edgewood Ave., Silver Spring, Md. (a)
Adams, Mr. Leland C., P. O. Box 341, Franklin, La. (bd)
Adams, Mr. R. J., 3102 Milby St., Wichita Falls, Texas (bh)
Aden, Mr. Arthur L., 61 Harvard Way Extension, Cambridge 63, Mass. (cd)
Alpert, Dr. Leo, 4857-B S. 28th St., Arlington, Va. (ceg)
Anderson, Mr. James R., 1950 Dryden St., Houston 5, Texas (c)
Anderson, Mr. Joseph B., Room 505, 1201 Thirteenth St., N. W., Washington 5, D. C. (c)
Anderson, Mr. William B., 352 Gundry Dr., Tyler Gardens, Falls Church, Va. (c)
Andre, Mr. Milo J., 6232 Ingleside Ave., Chicago 37, Ill. (c)
Andrews, Mr. James F., Apt. 23, 1848 Wyoming Ave., N. W., Washington 9, D. C. (c)
Arnold, Mr. Kingsland, P. O. Box 900, Dallas 1, Texas (abcdefgh)
Arnold, Mr. Vernon E., 1812 Ross Pl., Albuquerque, N. Mex. (g)
Aronow, Mr. Saul, U. S. Geological Survey, University Sta., Grand Forks, N. Dak. (g)
Atwood, Mr. William H., Jr., P. O. Box 23, Okemah, Okla. (ab)
Aubert, Mr. Eugene James, 2818 Erie St., S. E., Washington 20, D. C. (c)
Auten, Dr. John T., 111 Old Federal Bldg., Columbus 15, Ohio (g)
Badner, Mr. Julius, U. S. Weather Bureau, 1400 U. S. Court House, Chicago, Ill. (c)
Banfield, Dr. A. F., Behre Dolbear and Co., Room 963, 11 Broadway, New York, N. Y. (dg)
Barger, Dr. Gerald L., Agronomy Dept., Iowa State College, Ames, Iowa (c)
Barnidge, Mr. Thomas B., 5988 Lindenhurst Ave., Los Angeles 36, Calif.,(c)
Barth, Mr. Victor W., 2324 E. 49th St., Los Angeles 11, Calif. (g)
Bartlett, Mr. Vernell W., Camp Detrick, Frederick, Md. (c)
Barton, Prof. James R., Civil Engr. Dept., University of Utah, Salt Lake City, Utah (cg)
Bascom, Mr. Willard, 201 California Hall, University of California, Berkeley, Calif. (e)
Baudendistel, Mr. Martin E., U. S. Forest Service, Missoula, Mont. (g)
Beatty, Mr. Glenn H., 200 Tibet Road, Columbus 2, Ohio (cg)
Bediz, Mr. Pertev I., M. T. A. Enstitusu, Ankara, Turkey (b)
Beer, Mr. C. G., 6123 Faculty Ave., Bellflower, Calif. (cg)
Belmont, Mr. Arthur D., 55 Merced Ave., San Francisco, Calif. (cg)
Bennet, Mr. Geoffrey Carr, 5072 Tennyson St., Denver 12, Colo. (ceg)
Bentley, Mr. Mark T., P. O. Box 121, Whitesboro, Texas (a)
Beresford, Mr. Herbert W. D., 6301 Pillsbury Ave., Minneapolis 19, Minn. (c)
Berger, Mr. Marolf B., 2112 N. E. Eighteenth St., Oklahoma City 5, Okla. (g)
Bergman, Mr. Eugene E., 1574 Asbury Ave., Evanston, Ill. (dh)
Berry, Capt. Frederic A., Jr., Navy Weather Central, Washington 25, D. C. (c)
Biehler, Mr. William A., 2311 Piedmont Ave., Berkeley 4, Calif. (g)
Black, Mr. Arthur W., 210 E. Tenth Ave., Denver 3, Colo. (b)
Blanton, Mr. Sanky Lee, Jr., 119 Mason Farm Road, Chapel Hill, N. C. (e)
Blanchard, Mr. A., 3001 University Blvd., Houston 5, Texas (b)
Blewett, Mr. Stephen E., 2822 Grandeur Ave., Altadena, Calif. (c)
Blue, Lt. Col. Frank Lee, Jr., Engineer, Historical Div., OCE, Box 1715, Baltimore 3, Md. (eg)
Bobrovnikoff, Dr. N. T., Perkins Observatory, Delaware, Ohio (a)
Bodurtha, Mr. Frank R., Graduate House, Massachusetts Institute of Technology, Cambridge, Mass. (c)
Bohrer, Mr. Samuel, 4557 W. Pine St., St. Louis 5, Mo. (bg)
Bogert, Mr. Bernard O., 129 McCartney St., Easton, Pa. (dh)
Bonham, Mr. Lawrence D., 6838 Dorchester Ave., Chicago 37, Ill. (h)
Bonini, Mr. William E., Dept. of Geology, Princeton University, Princeton, N. J. (a)
Bonwit, Mr. Kenneth Stanley, 1103 Trenton Place, S. E., Washington 20, D. C. (b)
Bourke, Mr. Kenneth E., 17024 33rd Ave., S., Seattle 88, Wash. (c)
Bove, Mr. Bernard A., Jr., 3328th Trng. Squ., Box 336, Scott Air Force Base, Ill. (c)
Boyd, Mr. Thomas J., Jr., Apt. 204, 4213 Oglethorpe St., Hyattsville, Md. (cd)
Brooks, Dr. Douglas L., Opns. Eval. Group, Navy Dept., Washington, D. C. (a)

Brown, Mr. Delbert W., 112 1/1 Fifth Ave., Holdrege, Nebr. (gh)
Brown, Lt. Comdr. M. E., 5014 Ventnor Road, Washington 16, D. C. (a)
Browning, Mr. Frank H., 325 County City Bldg., Seattle 4, Wash. (e)
Bryan, Mr. Joseph G., 97 Green St., Melrose 76, Mass. (c)
Bunting, Mr. Donald C., 310 North Oak St., Gainsville, Fla. (cg)
Burgoyne, Dr. Edward E., 1501 Cherokee Pl., Bartlesville, Okla. (c)
Burzi, Mr. Angelo V. J., 416 E. 119th St., New York 35, N. Y. (c)
Bush, Mr. James, 2095 Union St., Brooklyn 12, N. Y. (e)
Byrd, Mr. Willie O., 129 Arden Road, Columbus 2, Ohio (a)
Carhart, Miss Grace M., Hunter College, 695 Park Ave., New York 21, N. Y. (f)
Carr, Mr. John H., 299 N. Adams St., Sierra Madre, Calif. (eg)
Carroll, Mr. Joel, Topographic Br., U. S. Geological Survey, Washington 25, D. C. (a)
Carsola, Mr. Alfred J., 51 Torrey Pines Homes, La Jolla, Calif. (efh)
Chalker, Mr. William Rogers, Box 218A, MIT Graduate House, Cambridge 39, Mass. (cg)
Chien, Mr. N., Room 722, International House, Berkeley 4, Calif. (eg)
Churchill, Mr. Heber B., 169 Columbia Heights, Brooklyn 2, N. Y. (b)
Clark, Mr. Robert A., P. O. Box 172, Smith Center, Kans. (ceg)
Clarke, Dr. George L., Biological Laboratories, Harvard University, Cambridge 38, Mass. (e)
Clarke, Mr. Robert F., c/o Flight Advisory Weather Serv., P. O. Box 361, Miami Springs, Fla. (c)
Coleman, Dr. Howard S., 428 Physics Bldg., University of Texas, Austin, Texas (c)
Colwell, Dr. Robert C., Martin Hall, Physics Dept., West Virginia University, Morgantown, W. Va. (c)
Cook, Mr. John C., Dept. of Geophysics, State College, Pa. (bd)
Cooper, Dr. Robert I. B., Dept. of Geodesy and Geophysics, University of Cambridge, Cambridge, England (bdef)
Cox, Mr. Robert O., 56 Alp Ave., Daly City 25, Calif. (c)
Cronin, Mr. Harold E., P. O. Box 214, College, Alaska (bd)
Cronin, Mr. James G., P. O. Box 45, Holdrege, Nebr. (abfg)
Crowe, Mr. Herbert C., Jr., 906 N. Eighth St., Terre Haute, Ind. (ce)
Culbertson, Mr. Thomas M., U. S. Geological Survey, 392 W. Fifteenth St., Austin, Texas (g)
Culler, Mr. Richard C., 303 Federal Bldg., Salt Lake City 1, Utah (cg)
Czuba, Mr. Walter T., 2789 Alvin Groom Court, Oakland 3, Calif. (cg)
Daniels, Mr. Eugene, 521 N. Henry St., Madison 3, Wis. (dg)
Darby, Mr. Thomas E., 2001 Gorman Ave., Waco Texas (h)
Davies, Mr. William E., 2311 N. Ninth St., Arlington, Va. (ag)
Davis, Mr. George H., U. S. Geological Survey, 1330 Jay St., Sacramento 4, Calif. (g)
Davis, Mr. Gordon E., U. S. Geological Survey, 445 N. Pennsylvania St., Indianapolis 4, Ind. (g)
Deeg, Mr. James J., 100 Lewiston Road, Dayton 9, Ohio (acd)
Dennis, Mr. Terence E., 538 Mission St. S., Pasadena, Calif. (b)
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SPECIAL ANNOUNCEMENTS

Thirty-First Annual Meeting--The Thirty-First Annual Meeting of AGU will be held in Washington, D. C., May 1-4, 1950. Sections and committees are at work laying plans for and arranging programs. Transmit any plans for papers that you may desire to present, or comments pertinent to the meeting to the appropriate Section Secretary or to the Office of the AGU, and watch the SPECIAL ANNOUNCEMENTS in subsequent issues for further information.

Twenty-Fifth Regional Meeting planned for Davis, California in February, 1950--Plans are under way for the Twenty-Fifth Regional Meeting to be held at Davis, California in February 1950. Thus far, only the Section of Hydrology is arranging a program, but other Sections have been invited to do likewise. Chairman for the Section of Hydrology is F. J. Veihmeyer of Davis. Suggestions or inquires relating to the meeting as it bears on hydrology should be sent to him. With regard to other sections, communications should be sent to the office of AGU in Washington. Watch the SPECIAL ANNOUNCEMENTS for further developments.

Triennial elections in 1950--Officers of the Union and its Sections are to be elected by mail ballot by the membership in March 1950. Procedures are to be the same as established in 1946 [see Trans. Dec. 1946, pp. 910-914] except (1) that the Section of Hydrology will follow the procedure of the Union and all of the other Sections in presenting a slate of "official nominees" that will be published in the December issue of the Transactions, with nominations by petition until January 31, in accordance with the procedure set up in 1946; and (2) that in Seismology 13 names must be on petitions. Nominating committees invite the suggestions of members, which may be sent to a member of the appropriate committee or to the office of AGU for forwarding. The Committees on Nominations designated are as follows:

Union: J. B. Macelwane, Chairman; Henry R. Aldrich; Merrill Bernard; Richard E. Fuller; and Charles A. Whitten
Geodesy: W. D. Sutcliffe, Chairman; John A. O'Keefe; and R. M. Wilson
Seismology: R. R. Bodle, Chairman; Beno Gutenberg; James B. Macelwane; and James T. Wilson
Meteorology: Charles F. Brooks, Chairman; C. W. Thornthwaite; R. H. Weightman; and H. R. Byers (ex officio)
Terrestrial Magnetism and Electricity: W. J. Rooney, Chairman; R. R. Bodle; C. W. Gartlein; L. H. Rumbaugh; and E. J. Workman
Oceanography: Athelstan Spilhaus, Chairman; Kenneth O. Emery; Robert B. Montgomery; Walter H. Munk; and John P. Tully
Volcanology: J. F. Schairer, Chairman; Howel Williams; and Harry H. Hess
Hydrology: R. M. Davenport, Chairman; Charles R. Hursh; R. M. Leggette; H. S. Riesbol; and Walter Wilson
Tectonophysics: Ernst Cloos, Chairman; L. H. Adams; and John N. Adkins

Fountain pen found at Annual Meeting --A valuable fountain pen was left at the main registration desk in the National Museum at the time of the Annual Meeting in April. The owner may recover this through the office of AGU.

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